



Original Article

Mitigation of single-event transients in high-frequency analog circuits using choke inductors

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ABSTRACT

Exposure to high-energy particles leads to a potential risk of generating single-event transients (SETs) in active devices of microelectronic circuits, compromising signal integrity. In order to mitigate the impact of SETs in the high-frequency analog circuits, we propose the use of choke inductors at the input and the output terminals, which provides low-impedance paths to transient currents that occupies low-frequency ranges. At high frequencies of operation, these choke inductors act as an open, thereby not affecting circuit performance. Through simulations and experiments using a low-noise amplifier (LNA) as a device under test, it was shown that the proposed structure effectively reduced sensitivity to SETs without degrading circuit performance. For quantitative comparison, reference LNA samples without choke inductors were prepared and analyzed as well. The proposed radiation-hardening-by-design approach offers improved reliability of analog circuits operating under radiation-intense environment.

1. Introduction

Electronics operating in extreme environment such as satellite applications or nuclear power plants, reliability issues associated with radiation effects have become critical. Regarding radiation effects, degradations arise from exposure to particles such as protons, neutrons, and high-energy electrons, consequently degrading lifetime or soft errors in the operation of circuits and systems [1,2]. For example, integrated circuits or systems typically experience leakage increase, gain reduction, and operational errors under radiation exposure [3]. Due to the various problems caused by ionizing particles, there is a demand for microelectronic circuits designed with radiation hardness to operate with high reliability [4–6].

Radiation effects on electronic devices and systems are categorized as three primary mechanisms: total-ionizing dose (TID), displacement damage (DD), and single-event effects (SEEs). TID effect denotes the degradation over a long period of time in electrical performance

parameters resulting from the generation of traps when positive charges are captured at the interface of insulators such as the MOS gate of integrated circuits (ICs) or systems. Consequently, as these degradations continue to accumulate, they can lead to component failure. DD refers to the mislocations or vacancies in the lattice structure due to irradiation, resulting in degradations in long-term device parameters [7–9]. Lastly, SEEs occur at random times and they are classified into various types such as single-event transients (SETs) and single-event upset (SEU) [10]. They occur when high-energy particles such as heavy ions collide with sensitive areas of the device, disrupting electrical operations and causing malfunctions [11,12]. The impact of SEE results in dynamic changes in the device or circuit. Whereas recovery is possible in many cases, severe damages resulting from heavy-ion strike are irrecoverable [10].

Several studies have addressed the issues of TID and SEEs. Some researchers have explored various techniques to mitigate SETs in flip-flop logic circuits [13–15] and others have studied

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radiation-hardened-by-design (RHBD) approaches in radio-frequency (RF) transceivers and component circuits such as a low-noise amplifier (LNA), a mixer, and a voltage-controlled oscillator [16–19]. Additionally, research has been conducted to mitigate SET through layout design [20–22]. Studies related to SEU in memory applications such as SRAM and NAND flash have also been conducted [23–25].

In this paper, we propose an RHBD technique in which choke inductors are integrated into the input and the output of RF or analog circuits to enhance immunity against SEEs. It is aimed to prove that the sensitivity of SETs is reduced by utilizing choke inductors in RF circuits. Section 2 discusses the structure of the proposed RHBD LNA and compares its performance parameters with that of the reference LNA. Section 3 conducts simulations to replicate SETs, using a dual double-exponential current source which models transients. The response of transients at the input and the output part of the circuit are also studied. In Section 4, transient response obtained from the laser experiment (two-photon absorption, TPA) is analyzed and compared with the simulations. In addition, by using the fast Fourier transform, the time-domain response is transformed into frequency spectrum for extracting more insight. Finally, in Section 5, the findings of this investigation are summarized.

2. RHBD LNA with choke inductors

A low-noise amplifier (LNA) is a key component used as a front-end gain stage in a receiver. Since its noise is dominant in determining the overall noise performance of the entire receiver, it is essential to achieve a low noise figure (NF) and a sufficient gain simultaneously [15,26]. In addition, providing matched impedances at the input and the output ports is important for minimizing reflections or ripples of the signal. The schematic of the proposed LNA with SEE mitigation is shown in Fig. 1. It is based on the cascode configuration, which offers good isolation between the input and the output terminals, greater transistor output impedance, and improved voltage gain [15,27]. The lower transistor Q_1 is configured as a common-emitter (CE) stage and the upper transistor Q_2 forms a common-base (CB) stage.

In this specific design, the CE transistor operates in the forward mode to maximize circuit performance, whereas the CB transistor is in the inverse mode for reducing sensitivity to SETs by switching the electrical connections of the collector and the emitter [5]. Because the transconductance (g_m) of the CE transistor determines the overall gain of the amplifier, it operates in the forward-active bias to obtain better gain. At the same time, greater gain helps lower the NF of the LNA simultaneously. On the other hand, the upper transistor serves as a current-buffer stage, it can be chosen to operate in the inverse mode in

which the electrical connection of the collector and the emitter terminals are swapped. The inverse mode has been known to exhibit reduced sensitivity against SETs due to its internal barrier to the excess charges of transients [18]. The LNA was designed to operate at the center frequency of 2.4 GHz. For impedance matching at the input, the values of the base inductor L_B , the emitter inductor L_E , and the base-to-emitter capacitor C_B were optimized to present 50 Ω , whereas the input capacitor C_I was an AC short. At the output, the collector inductor L_C and resistor R_C and the output capacitor C_O were tuned for matching. In addition to these components, choke inductors L_{RFCI} and L_{RFO} were connected in parallel at the input and the output ports, respectively.

Fig. 2 shows the simulation conducted to examine the performance difference between the reference LNA and the proposed LNA, as well as the changes in the peak transient current at the input and output, with inductance values ranging from 1 to 10 nH. To account for the area increase due to the choke inductors, the simulations were limited to a maximum inductance of 10 nH. The peak transient currents at the input and output were measured by summing the absolute values of each. Additionally, to quantify the similarity in performance to the reference LNA at the operating frequency, the absolute differences between S_{11} , S_{22} , S_{21} , and NF for the proposed and reference LNAs were calculated and summed. The results show that as the inductance increases, the total peak transient current initially rose but began to more or less saturate from 7 nH onward. On the other hand, the sum of the absolute performance differences from the reference LNA decreased as the inductance increased. Since lower values for both peak transient current and the absolute sum of performance differences with the reference LNA are desirable, an inductance value of 9.2 nH was determined to be suitable for balancing peak transient current and LNA performance.

Since the impedance of the choke inductors are small, they are effective in sinking DC or low-frequency components of transients generated from the transistors. By allocating large inductances, however, their impact on the high-frequency operation can be minimized, as they are seen as open. Thus, the choke inductors provide a low-pass-filter function to the ground, selectively passing transient signal components only. At the same time, the choke inductors act as high-pass filters to the input and output ports. In Table 1, the size of transistors and the values of circuit components are listed. The proposed RHBD LNA and the reference one have the same transistor size, whereas there are differences in the use of choke inductors and some values of matching elements. The average quality factor (Q-factor) of the inductors is approximately 12, which is suitable for the operating frequency of 2.4 GHz.

The key performance parameters of the LNA include power gain

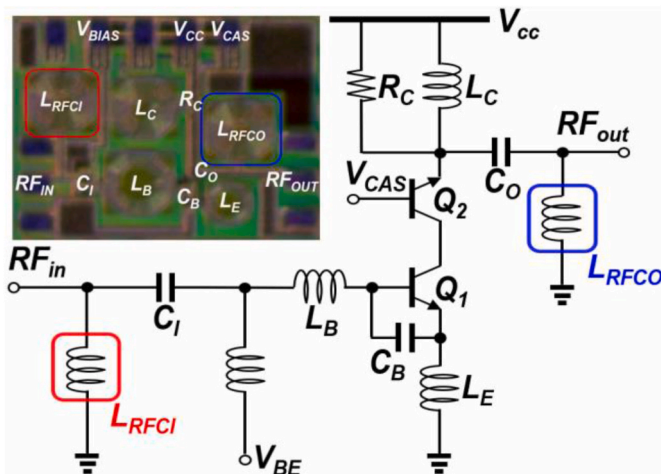


Fig. 1. Schematic of the proposed RHBD low-noise amplifier (LNA) with choke inductors and a chip micrograph.

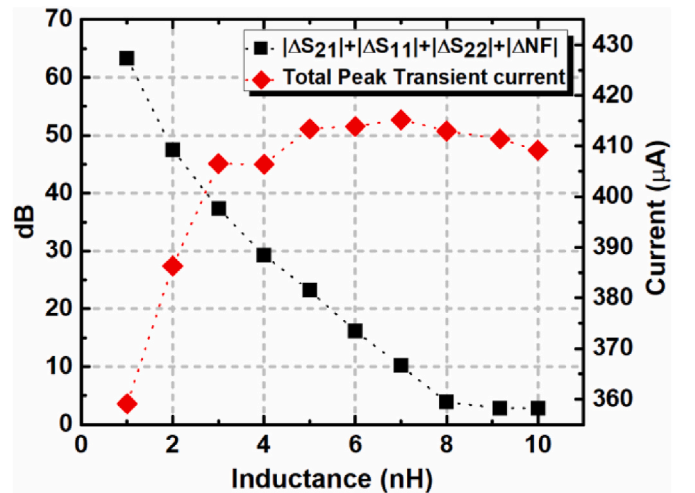


Fig. 2. Changes in the total peak transient current and performance similarity to the reference LNA with variations in the choke inductor inductance.

Table 1
Size and component values of the LNAs.

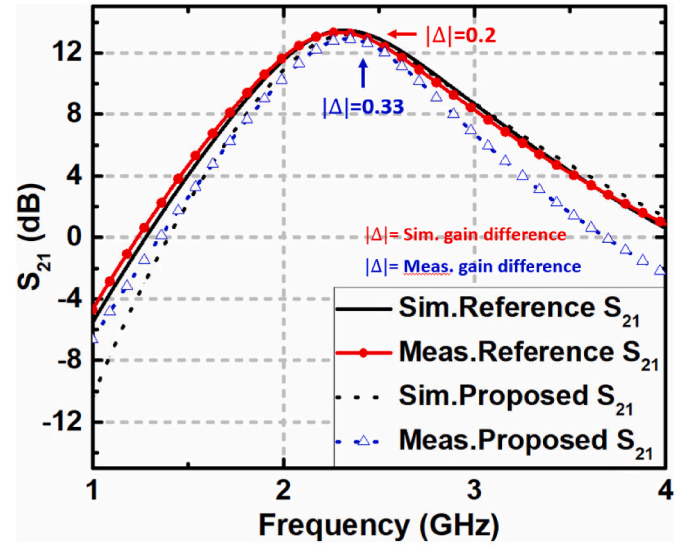
Components	Unit	Reference LNA	Proposed RHBD LNA
L_{RFCI} (Q)	nH	—	9.2 (12.4)
C_i	pF	6.7	6.7
L_B (Q)	nH	6.4 (14.7)	5.4 (14.4)
C_B	fF	560	560
L_E (Q)	pH	990 (8.8)	990 (8.8)
R_C	Ω	930	930
L_C (Q)	nH	8.5 (12.7)	8.5 (12.7)
C_O	fF	435	405
L_{RFCO} (Q)	nH	—	9.2 (12.4)
Q_1 [W, L]	nm, μ m	120, 5	120, 5
Q_2 [W, L]	nm, μ m	120, 5	120, 5

(S_{21}), NF, input matching (S_{11}), and output matching (S_{22}). The circuit was designed and optimized, using GlobalFoundries 8HP 130 nm SiGe BiCMOS technology, and the chip micrograph of the LNA was shown in the inset in Fig. 1. Both the proposed RHBD LNA samples and the reference version without choke inductors were fabricated for a comparison study. The RF performance of the LNAs was characterized, using a two-port network analyzer (Agilent PNA E8361C) and a probe station for scattering parameters. NF was measured, using a spectrum analyzer (Agilent PXA N9030A) and a noise source (Agilent N4002A) [28].

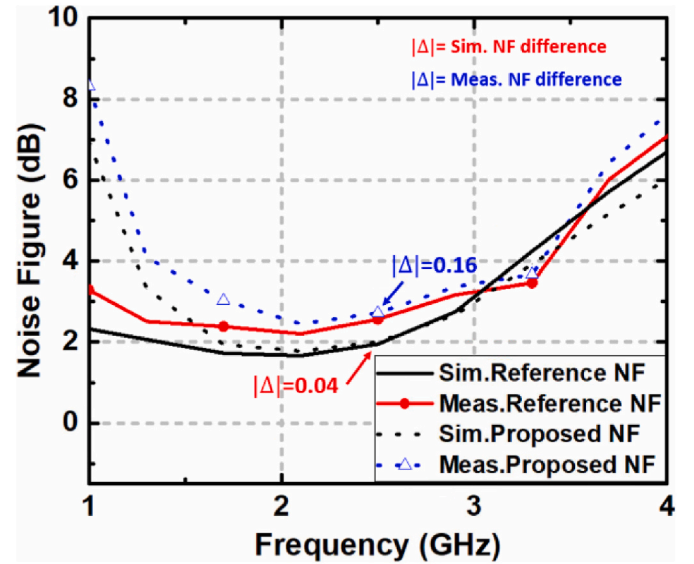
Fig. 3 presents the RF performance based on the simulation and chip measurement results of the proposed RHBD LNA and the reference LNA. At the operating frequency of 2.4 GHz, the performance differences between the simulation and actual measurements for the reference LNA are as follows, with S_{21} differing by 0.24, NF by 0.62, S_{11} by 7.04, and S_{22} by 3.2. For the proposed LNA, the differences are 0.3 for S_{21} , 0.72 for NF, 11.04 for S_{11} , and 4.6 for S_{22} . Fig. 3(a) illustrates the gain (S_{21}) versus frequency. At the operating frequency, the difference between the reference and proposed LNAs in simulation is 0.2, while in actual measurements, the difference is 0.33. Fig. 3(b) presents the NF versus frequency. At 2.4 GHz, the discrepancy between the reference and proposed LNAs in simulation is 0.04, while the difference in actual measurements is 0.16. At frequencies lower operating frequency, more significant differences are observed, which is due to the fact that the choke inductors affect the transfer characteristics of the circuit operation. Therefore, selecting appropriate inductance based on the center frequency of the LNA is essential to maintain consistent gain and noise performance, as shown in Fig. 4.

Fig. 4(a) and (b) show the input impedance matching (S_{11}) and output impedance matching (S_{22}) as a function of frequency, respectively. In the simulation results, both the reference and proposed LNAs exhibit a difference of 1 for S_{11} and S_{22} . In actual measurements, the difference in S_{11} between the two circuits is 4.4, while the difference in S_{22} is 0.01. These discrepancies may be attributed to the accuracy of inductor modeling. Accurate identification of losses and parasitic elements, especially in high-frequency bands, is necessary, but parasitic resistances, inductive coupling, and substrate losses increase with frequency, which complicates inductor modeling further. Additionally, parasitic impedances associated interconnects and measurement setup may contribute to these differences in S-parameter and NF measurements. Finally, the use of inverse-mode SiGe HBT, which is not assumed in typical design-kit models, may add some deviations. These limitations lead to some discrepancies between simulation and actual measurements.

In the proposed LNA structure, choke inductors are connected in parallel between the input and output nodes and ground, respectively, which can affect input and output matching. Therefore, in the proposed LNA, the inductance of L_B , one of the components in the input matching network, was reduced by 15 % to 5.4 nH compared to the reference LNA, and the capacitance of C_O , one of the components in the output matching network, was adjusted to 405 pF, a decrease of 7 %. As a result, S_{11} and S_{22} response of the proposed LNA is similar to that of the reference LNA.



(a)



(b)

Fig. 3. (a) S_{21} and (b) NF of the reference LNA and proposed LNA versus frequency in simulation results and chip measurements.

Thus, based on the comparison of S-parameters and NF results, it is observed that the inclusion of choke inductors leads to minimal changes in the performance at the operating frequency, but acceptable variations in other frequency ranges.

Table 2 summarizes the measured spot performance of S-parameters and NF at the operation frequency of 2.4 GHz. Both the proposed and the reference LNAs exhibit slight differences in comparison with the simulation results, verifying that minimal changes in performance with the use of choke inductors. Table 2 compares the performance of the LNA designed in this study with LNAs designed in the literature. Compared with the performance of LNAs in Refs. [29–31], the proposed LNA demonstrates comparable performance in almost all metrics. Therefore, it can be concluded that the proposed LNA is competitive with other design examples. Another aspect of the circuit design to consider is the chip size. Compared to the reference LNA, which has an area of 0.336 μm^2 without pads, the proposed LNA consumes a larger area due to the use of choke inductors, resulting in an increase of 0.076 μm^2 in chip area. This represents approximately a 22.6 % increase compared with the area of the reference LNA. The sensitivity of the LNAs to SETs will be

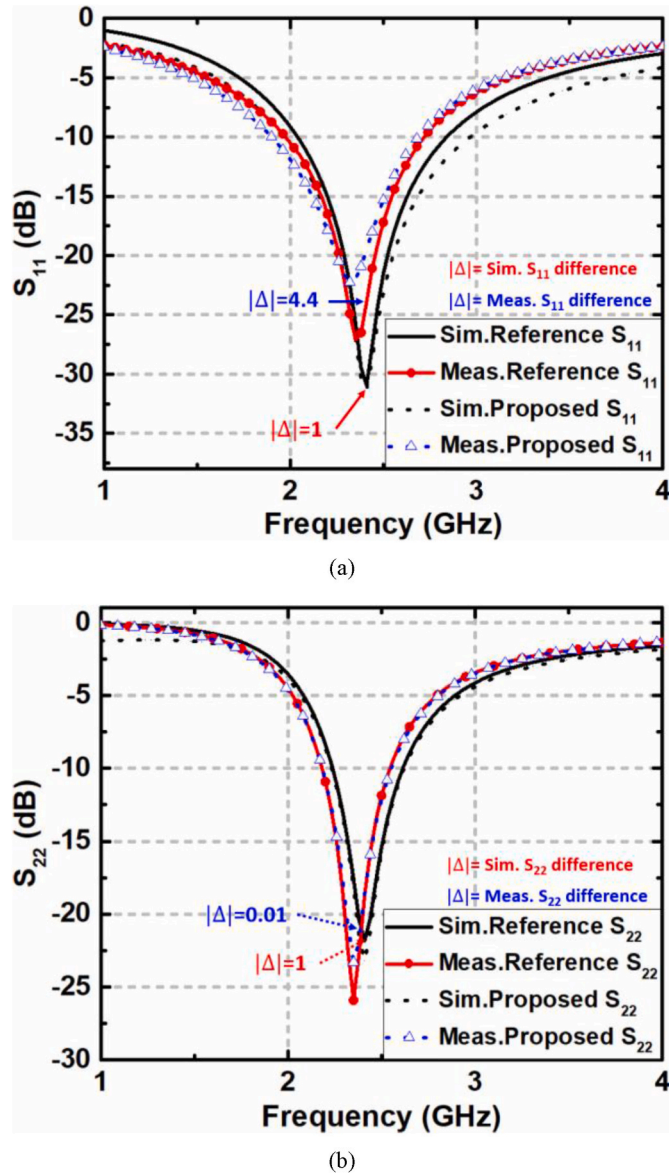


Fig. 4. (a) Input impedance matching (S_{11}) and (b) output impedance matching (S_{22}) of the reference LNA and proposed LNA versus frequency in simulation results and chip measurements.

Table 2
Measured performance of the LNAs.

Parameter	Freq. [GHz]	S_{21} [dB]	S_{11} [dB]	S_{22} [dB]	NF [dB]	Power [mW]	Area [μm^2]
Ref. LNA	2.4	13.3	-31	-22	1.85	2.37	0.336
Proposed LNA	2.4	13.1	-32	-23	1.89	2.37	0.412
[29]	5.7	11.45	-14	-17	3.4	3.96	0.855
[30]	2.4	13	-13	-10	3.6	6.5	0.799
[31]	2.14	14.5	-15.2	-11	1.97	7.5	0.544

presented in the next section.

3. Analysis and simulation of transient response

To analyze the sensitivity of the proposed RHBD LNA to SETs, a simplified LNA structure was used. This LNA is divided into input and

output matching network sections, with SET current models replacing the transistors. For SET current modeling in the simulation environment, the commonly used double-exponential current source from other studies was initially considered. The SET current obtained using this source, however, was not accurate enough. Therefore, the dual double-exponential current source was used, which connects two double-exponential current sources in parallel, as proposed in Ref. [32]. Because this current source was designed to model SET currents in logic circuits, it could not be directly applied to the high-speed analog circuits, as the SET current characteristics and their impact on the circuit operation differ. Consequently, both current sources in the dual double-exponential model were configured to model peak currents over short durations based on the experimental results. Through this approach, it was possible to model SETs similar to two-photon-absorption (TPA) results.

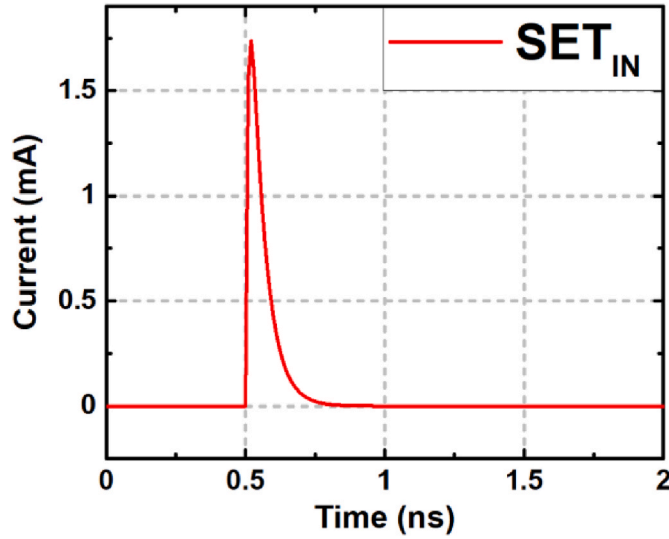
The dual double-exponential current source comprises several parameters and constants, such as peak current level, rise time, and fall time. Defining the SET current models connected to the input and output matching sections as Input SET Current Models 1 and 2 and Output SET Current Models 1 and 2. Input SET Current Models 1 and 2 have a current peak of 1.68 mA, rise and fall start times of 4 ns and 4.0006 ns, and rise and fall time constants of 130 ps, 90 ps, and 40 ps, 12 ps, respectively. Similarly, Output SET Current Models 1 and 2 have a current peak of 2.4 mA, rise and fall start times of 4 ns and 4.0006 ns, and rise and fall time constants of 4 ps, 6.2 ps, and 3.6 ps, 5 ps, respectively.

Whereas the TPA setup parameters, such as laser pulse energy, duration, and focal point, determine the photon absorption and subsequent SET induction, the double-exponential current source parameters such as peak current, rise time, fall time, and time constants are specifically chosen to model the transient current waveform resulting from SETs in the simulation environment. These two parameter sets differ due to the distinct nature of the physical TPA setup and the simulated current modeling. For a modeling purpose, we configured the double-exponential current source to replicate the SET waveform characteristics observed in TPA experiments, ensuring the simulated response aligns as closely as possible with experimental results. This approach allows us to maintain consistency between the simulation and experimental observations, despite the inherent differences in their respective parameter sets.

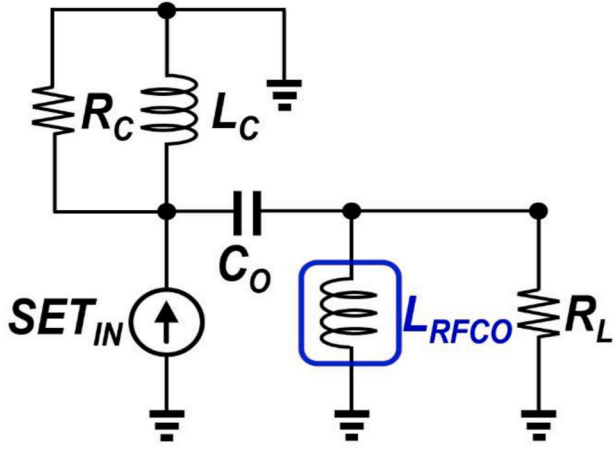
Fig. 5(a) demonstrates a shape of the dual double-exponential source used in the simulations of the circuit response due to SETs. For example, the schematic of the output-transient simulation is presented in Fig. 5 (b). Because the transients are considered as a small-signal current-input source and the output matching network is passive and linear, the small-signal equivalent circuit can be constructed accordingly. V_{CC} was AC grounded and the current flowing through the load resistor R_L was monitored. In a similarly, the input network was configured as a small-signal circuit that contained matching elements of L_{RFCL} , C_L , L_B , C_B , and L_E , and a modeled double-exponential current source.

Fig. 6 shows the transient response at the input terminal of the LNAs when the CE transistor Q_1 is affected by the SEE. In the place of Q_1 the SET model was connected and the changes were captured. When the circuit is under DC bias conditions, the resulting response is shown in Fig. 6(a). In comparison with the reference LNA, the proposed RHBD LNA exhibits about 15 % and 10 % reductions in transient peaks and durations, respectively. Fig. 6(b) presents the transient response due to SETs under AC operation. In this simulation, transient currents occur while the input signal with an RF power of -45 dBm and a frequency of 2.4 GHz is driving the LNA. The proposed LNA shows a lower peak (about 12 %) and a shorter recovery time than those of the reference circuit with the help of the low impedance associated with the shunt choke inductor.

In Fig. 7, the simulated transient response at the output terminal is shown for both LNAs. The CB transistor Q_2 is assumed to be under SEE and generates a double-exponential transient current toward the output



(a)

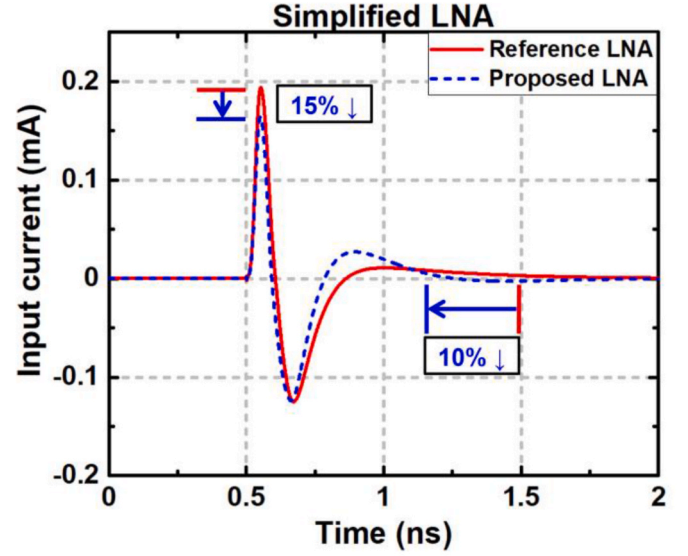


(b)

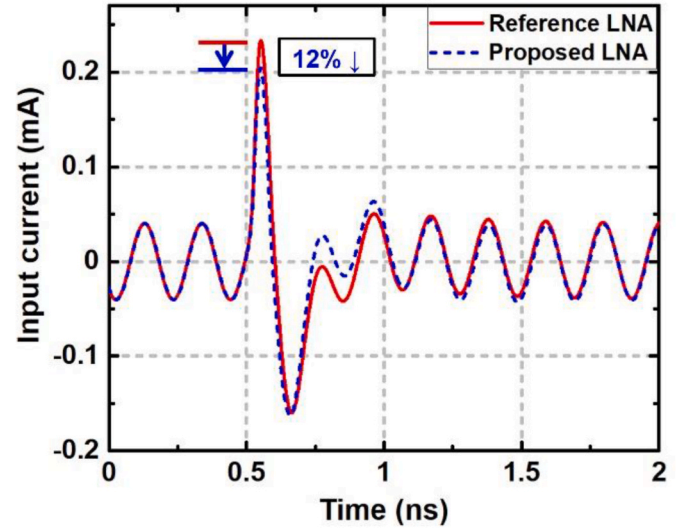
Fig. 5. (a) Double-exponential-based transient-current model used in this work (b) Simplified output matching network of the proposed LNA with a choke inductor.

matching network. For simplicity, the bottom CE transistor Q_1 and the input-matching part of the circuit have been removed in this simulation setup. Fig. 7(a) exhibits the variations of the output current with the transients when only DC bias conditions are applied to the circuit. Strictly speaking, all DC currents and voltages are zero in the small-signal equivalent circuit. In comparison with the reference LNA, the proposed LNA shows significant reductions of 28 % and 15 % in negative and positive peaks, respectively. This result is different from the transient response under DC, where only the positive peak is reduced. In Fig. 7(b), an RF signal of -45 dBm and 2.4 GHz is applied to the circuit, generating transient response. Similar to the DC case, the peaks of the output current were mitigated by 27 % and 14 % in both negative and positive values, respectively. On the other hand, there were no noticeable difference in the overall recovery characteristics in both the proposed and reference LNAs. As shown in the inset of Fig. 7(b), the impact of transients is much less in transient duration.

The simulation results in Figs. 6 and 7 indicate that the use of choke inductors is effective in mitigating sensitivity to SET in terms of peaks and duration times, meaning that low impedances associated chokes provide current-sinking paths to ground. It is worth noting that the actual improvements in transient response depend on the specific configuration of the network. For example, at the input, the injected



(a)



(b)

Fig. 6. Simulated response of the proposed RHBD LNA and the reference LNA at the input terminal when the CE transistor generates transients (a) Under DC bias conditions (b) With an AC input signal.

transient current sees an inductor and a capacitor in series before arriving at the input terminal. Thus, the voltage at the source resistance, which is the output impedance of the driving stage (or an antenna in a receiver), exhibits a positive spike at the beginning, as shown in Fig. 6 (a). In contrast, at the output, the transient current sees a shunt inductor L_C , leading the output current to flow from the load resistor. Unlike the transient response at the input, the output terminal generates a negative spike initially, and then a positive spike appears. With regard to changes in the transient peaks, since the emitter inductor L_E already presents a low impedance to ground, only a small portion of transient currents can flow through L_{RFCO} . Therefore, the peak reduction at the input was less than the output terminal.

It is important to address the potential limitations of the simulations conducted in this Section. First, the use of the double-exponential currents for modeling transients do not fully capture accurate response of the circuit, even though its profile is similar to device-level transients. Because an ideal source always presents the same current shape regardless of the components (i.e., impedances) connected to the source,

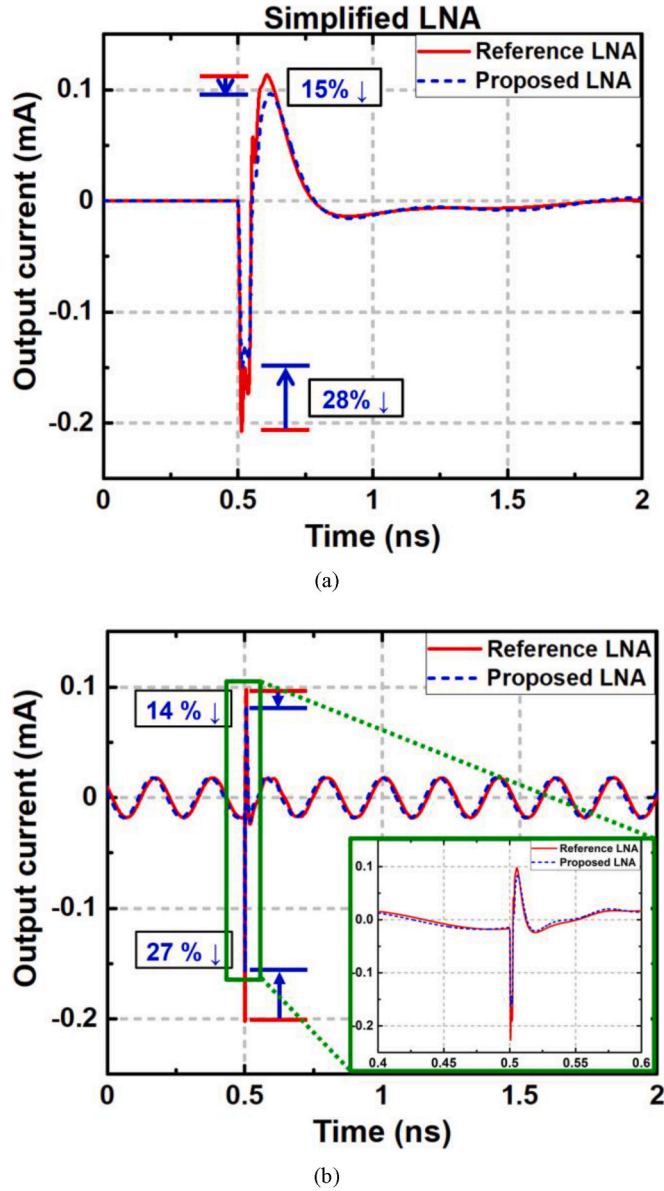


Fig. 7. Simulated response of the proposed RHBD LNA and the reference LNA at the output terminal when the CB transistor generates transients (a) Under DC bias conditions (b) With an AC input signal.

no interactions can be reflected with the model in circuit simulations. Second, the absence of the transistors in the simulation setup may lead to errors in obtaining transient response. When SEE occurs, a victim transistor is virtually shorted to have no voltage differences among base, emitter, collector, sub-collector, and substrate. As time goes, the internal voltages are developed to recover its initial bias conditions. These behaviors, however, are not reproducible with the transistor models in a typical process design kit. Lastly, the modification of the original circuit structure can change the transient response as well. In the previous simulations, the entire circuit structure was decomposed into two parts to study the sensitivity at the input and the output each, but again, potential coupling effects between these two parts need to be included for more accurate results. In the next Section, simulation results will be further investigated through the laser-based radiation experiments.

4. Radiation experiment results and discussion

With the LNA samples, radiation experiments were conducted to

study the transient response of the circuits. In order to induce SETs from the LNA chips, the laser-based setup was used for a pulsed-laser-based two-photon-absorption (TPA) test at the US Naval Research Laboratory [33]. The generated pulses had a wavelength of 1260 nm, a duration of 150 fs, a full-width at half-maximum (FWHM) focused spot size of 1.1 μm , an energy of 1.2 nJ, and a pulse repetition rate of 1 kHz. In addition, the laser light was focused on the center of SiGe HBTs so that charge-generation volume covered pn junctions of devices. To capture transient response, samples were attached to printed circuit boards and pads were connected through wire bonds. For biasing, a power supply of 2.5 V was used for V_{CC} and V_{CAS} , and V_{BE} was set as 0.79 V via a current mirror with a reference current of 0.73 mA. The time-domain transient results were captured using a high-speed oscilloscope (Tektronix DPO71254). Using this measurement setup, transient response of LNAs under DC bias conditions were measured.

Similar to the simulation conditions in Section 3, the lasers were directed to the CE stage of both LNAs to induce input transients. Fig. 8 illustrates the results of transient current measurements from the TPA experiment. Fig. 8(a) shows the input transient currents of both circuits

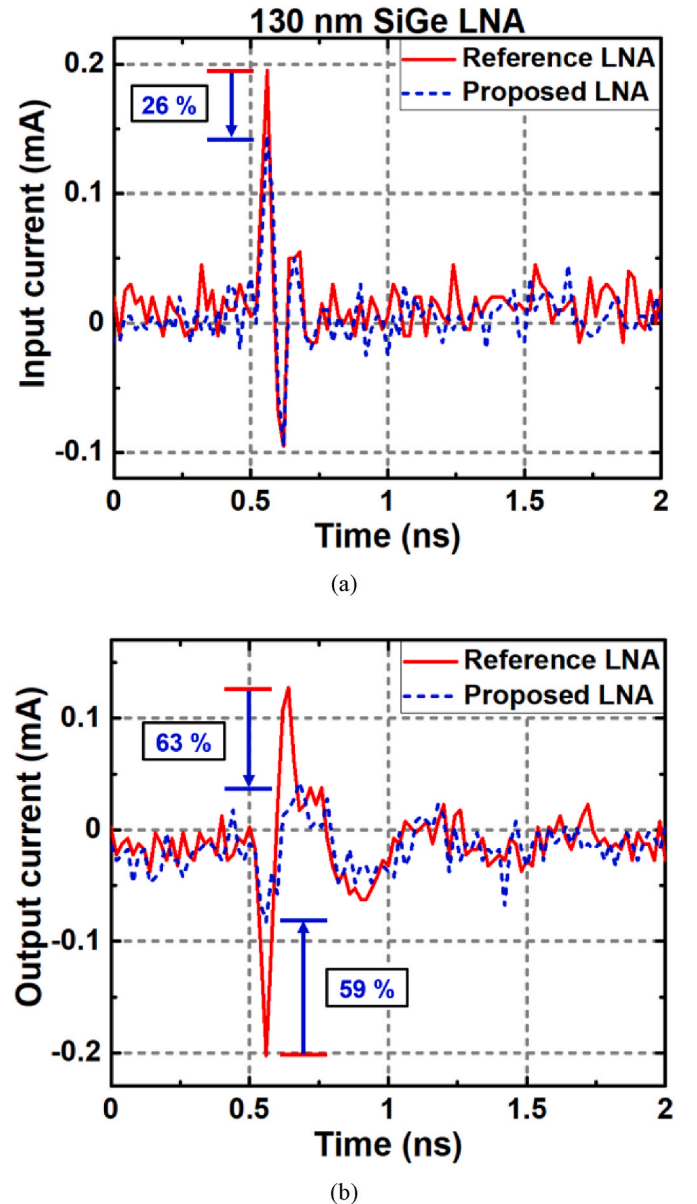


Fig. 8. SEE experiment results (a) Transient response at the input under CE strike (b) Transient response at the output under CB strike.

when the laser beam was focused on the bottom transistor Q_1 of the main branch. It is observed that the proposed LNA exhibits a reduction of 26 % in transient peaks compared to the reference LNA. Fig. 8 (b) shows the output transient current measured when the TPA laser beam was focused on the CB stage. The proposed RHBD LNA with choke inductors shows a mitigation of 59 % and 63 % in negative and positive peaks, respectively, compared to the reference one. Regarding transient duration times, the measured response reveals some differences. Whereas the simulated duration was reduced by about 10 % in the proposed LNA, however, the transient duration of both LNAs was almost similar about 0.3 ns. Since the noise currents existing in the measurement environment were added on top of the transient, it was difficult to separate those two signal components. Thus, further investigations are required to analyze timing response due to SETs.

In order to analyze the transient response in the frequency domain, the fast Fourier transform (FFT) was used to time-domain results. First, the transient-current profile was first converted to an instantaneous power, using the standard impedance of 50 Ω , and then, the FFT was applied to obtain power spectral density on the frequency axis. The final results of the input and at the output response are plotted in Fig. 9(a) and (b), respectively. It should be noted that due to noise present in the measurement setup, spectral density at around DC (including very low frequencies) may not represent the actual transient response of the circuit. Therefore, comparing peaks at around DC needs further detailed investigations. The overall frequency response of transients was observed above frequencies above 50 MHz (except DC) and below about 550 MHz, indicating the influence SET affects low-frequency ranges, which were similar for both the reference and the proposed RHBD LNAs. The measured peaks except DC were at around 400 MHz and 125 MHz in the input and the output spectrum, respectively. As expected from Fig. 8, reductions in the frequency domain were greater in the output transients than the input case.

A quantitative comparison of the current spectral density is summarized in Table 3. The average magnitudes of the reference and proposed LNAs at the input between 0 and 1.25 GHz are -47.3 mA and -48.6 mA, respectively, whereas at the output they are -46.8 mA and -49.8 mA, respectively. Transient at input at DC has a smaller value of -9.3 for the proposed LNA than the reference LNA, and peak at input and peak at output except DC has a smaller value of -3.3 and -3.8 for the proposed LNA than the reference LNA, respectively. FFT decomposes the amplitude of a given input signal into complex coefficients of each frequency component. If the current peak is smaller in the time domain, the resulting FFT amplitude will be smaller in the frequency domain as well. On the other hand, the transient output at DC is 4.2 higher in the proposed LNA, which may be combined effects of the noise sources associated with the choke inductors, impedance changes at low frequencies, sensitivity differences to the power-supply fluctuations.

Upon comparing the simulation and the experiment results, it is evident that the proposed LNA effectively reduces transient peaks at both the input and the output terminals. The greater reduction at the output than the input can be attributed to the difference network configurations. When it comes to a general application of the proposed idea, the following aspects should be considered. First, because the fundamental structure of using choke inductors have similarities with the protection circuitry of electrostatic discharge (ESD), existing designs can be modified for the reduction of transients if their frequency characteristics satisfy requirements. Second, for wideband circuits covering from low-frequency ranges, the on-chip choke inductors might not provide enough inductances. The use of off-chip choke inductors would provide better mitigation than on-chip counterparts due to large available inductances. Lastly, depending on the center frequency of the target circuit, the actual choke inductance can be obtained from the transmission-line-based structures. For example, high-frequency circuits that operate at 100 GHz ranges or above, spiral inductors can be seen as capacitive elements due to the limitation of quality factors. In this case, the use of open or short stubs would be a viable approach.

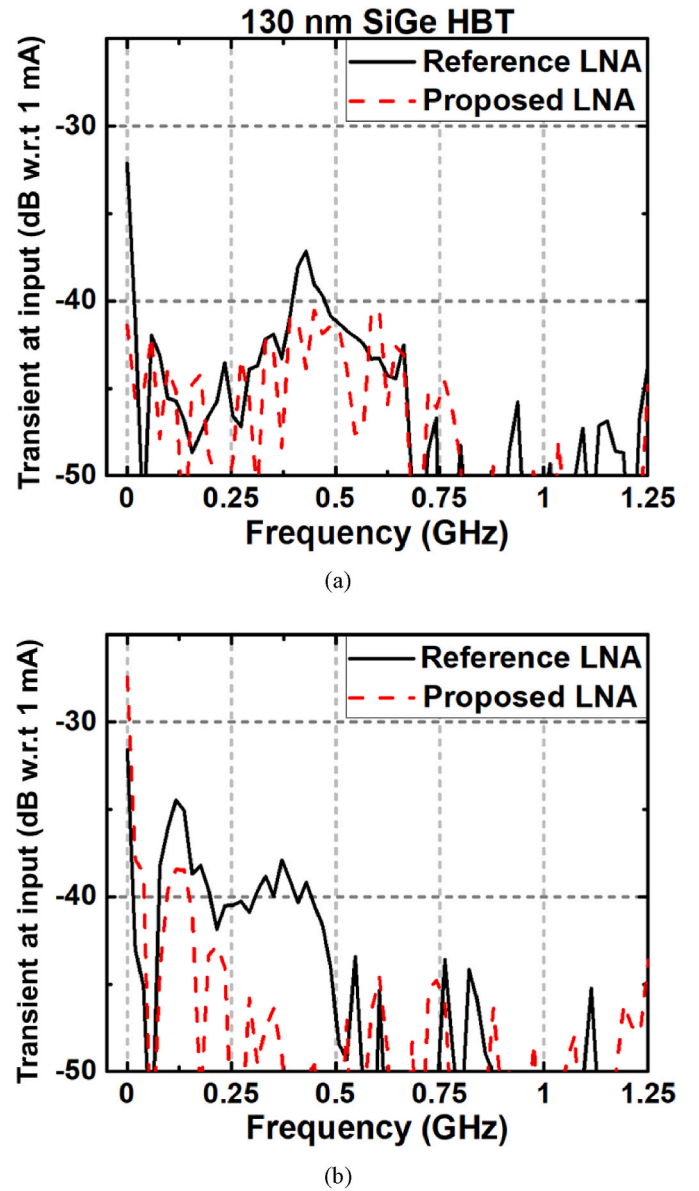


Fig. 9. Frequency-domain response of transients obtained by the fast Fourier transform. Current spectral density plotted in the unit of dB with reference to 1 mA. (a) Transient response at the input terminal under CE strike (b) Transient response at the input terminal under CB strike.

Table 3

Comparison of transient currents after FFT.

	Reference LNA (mA)	Proposed LNA (mA)
Transient at input (DC)	-32.1	-41.4
Transient at output (DC)	-31.6	-27.4
Peak at input except DC	-37.5	-40.8
Peak at output except DC	-34.4	-38.2
Average input transients	-47.3	-48.6
Average output transients	-46.8	-49.8

In the proposed RHBD LNA, only a few component values were slightly modified to keep the parameters of the input- and output-matching elements as close as possible to those of the reference LNA. If the matching network values were adjusted more extensively with a focus on performance optimization, however, both SET mitigation and circuit performance could be further enhanced. In addition, whereas this study uses an LNA as a high-frequency analog circuit, the RHBD

technique employing choke inductors could be applied to other types of high-frequency analog circuits, such as oscillators, mixers, or switches. On the other hand, there may be concerns regarding an increased area due to the inclusion of additional (choke) inductors. The overall overhead in terms of chip area without pads was about 22.6 %. In contrast, when considering the total area including pads for standalone chip design, the reference LNA occupies $0.840 \mu\text{m}^2$, whereas the proposed LNA occupies $0.885 \mu\text{m}^2$, indicating only a 5.3 % increase. Therefore, this demonstrates that the additional chip area as a tradeoff may be acceptable. In conclusion, the proposed RHBD technique is a viable technique for enhancing radiation hardness in high-frequency analog circuits.

5. Conclusion

In this work, the use of choke inductors connected in parallel to input and output terminals in analog or high-frequency circuits is proposed for the mitigation of single-event transients. Chokes inductors are chosen to have a high impedance at the frequency of operation, while exhibiting very low impedance for generated transients. By breaking the circuit into the input and the output matching parts and using the double-exponential transient-current model, the effectiveness of the proposed radiation-hardening-by-design technique has been demonstrated. In addition, the pulsed-laser-based two-photon absorption testing verifies the simulation results experimentally. For more in-depth understanding of transient response, time- and frequency-domain characteristics are studied.

CRediT authorship contribution statement

Jongho Lee: Writing – review & editing, Writing – original draft, Investigation. **Taeyeong Kim:** Methodology, Formal analysis. **Adrian Ildefonso:** Resources, Investigation. **Ani Khachatrian:** Resources, Methodology. **Dale McMorro:** Resources, Project administration. **Moon-Kyu Cho:** Validation, Methodology, Investigation, Formal analysis. **John D. Cressler:** Supervision, Project administration, Methodology. **Ilho Myeong:** Investigation, Methodology, Resources, Writing – review & editing. **Ickhyun Song:** Writing – review & editing, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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