Analysis of a redundant input stage for mitigating radiation effects on a two-stages Miller compensated Operational Amplifiers

Tássio Côrtes Cavalcante[1] and Lester Abreu Faria[2]
[1]Institute for Advanced Studies (IEAv), São José dos Campos/SP – Brazil
Aeronautics Institute of Technology (ITA), São José dos Campos/SP – Brazil

***Abstract* – In the context of Defense applications, high-performance and reliable systems are required in order to assure that no failures will occur when protecting a country's sovereignty. In the last years, the dependence on imported technological goods has increased in Brazil, as the technology advances continuously, and many embargoes have hindered the development of critical areas. One of these areas is the spatial area, and more specifically, the design of *rad-hard* systems for spatial applications. Operational Amplifiers (OpAmps) are one of the basic building cells on analog integrated circuits, being used for many different applications. However, for them to work properly, they need a good matching of the transistors, which make them prone to fail with radiation. This work presents a strategy for reducing this impact of radiation on the Two-stage-Miller-compensated OpAmp by duplicating its input stage. LTSpice software was used for simulation using 0.35µm CMOS technology process C35B4C3 of AustriMicroSystems and results show that the redundant OpAmp presents a better performance than the traditional one. The device performance was verified positively, showing a high potential to practical implementations.**

***Keywords* – Operational amplifiers, Radiation Effects, Reliability.**

I. Introduction

In the context of Defense applications, high-performance and reliable systems are required in order to assure that no failures will occur when protecting a country's sovereignty. In the last years, the dependence on imported technological goods has increased in Brazil, as the technology advances continuously, and many embargoes have hindered the development of critical areas. One of these areas is the spatial area.

One of the important technologies regarding the spatial area is the radiation hardening, i.e., developing systems that are tolerant to radiation (which is present in space). State-of-art technologies on the area are the ones which can continue working during a whole spatial mission and are the ones which are commonly of restricted access. Therefore, such technology must be developed by the very country which intends to use it on its projects.

Operational amplifiers (OpAmps) are one the basic cell in almost every analog integrated electronic circuit, because of their multiple usage. They require a proper design matching many transistors of the project for them to work accordingly to the functionalities and specifications of each project. Hence, they are very prone to fail with radiation, as mismatches will start to occur. Therefore, a design of an OpAmp which is radiation-hardened (or *rad-hard*) must be such that when a transistor mismatch occurs the system is not completely affected.

This paper presents a strategy for reducing the impact of radiation on the traditional Two-stage-Miller-compensated OpAmp (Fig. 1). The strategy of redundancy is very common when dealing with rad-hard digital circuits, mainly the use of TMR (Triple Modular Redundancy), and this approach is the same used here, but in an analog device. The redundant design presented in this work consists of a duplication of the input stage of this traditional OpAmp, which is one of the critical stages for an OpAmp to work properly and, thus, a duplicated structure reduces the effects of radiation on the device.

Some simulations were held in which the transistors parameters (threshold voltage, mobility and drain-source leakage current) are changed, simulating the radiation effects on a transistor, and the device performance was analyzed in these different scenarios. Two different cases were considered: i) when all NMOS transistors of the device are affected equally and ii) when there is a mismatch among some NMOS transistors. The analysis of these two effects has shown that the redundant design achieved a better performance than the traditional one, which evidences the competitive level of our work and its high potential to be practically implemented.

II. Electrical Design

Two different topologies were analyzed in this work. The first one (called traditional OpAmp) is the traditional two-stage Operational Amplifier with Miller compensation, which can be seen in Fig.1. The second one (called Redundant OpAmp) is based on the same topology, but with a redundant input stage, which can be seen in Fig.2. Both projects were developed using 0.35µm CMOS technology libraries of AustriaMicroSystems ($V_{DD} = 3.3V$) and previously tested through simulations using the software LTSpice with a load of 1pF.

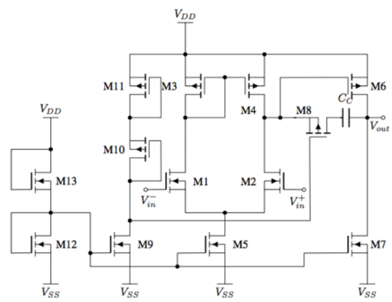

Fig.1. Schematic diagram of the traditional Operational Amplifier design topology.

A. *Traditional OpAmp project*

This design was based on basic and well-known OpAmp equations and topology, already presented in [1], followed by optimization processes focusing on increased slew rate and gain bandwidth. It was detailed in a previous work [2]. There is a main difference between the topology used in [2] and the one presented here. Transistor M12 and M13 in [2] are joined together here (called M12) to form one single transistor, whose width is the sum of the two and, thus, M14 in [2] becomes M13. Table I shows the dimensions of the transistors used for the design. The compensation capacitor was Cc=1pF.

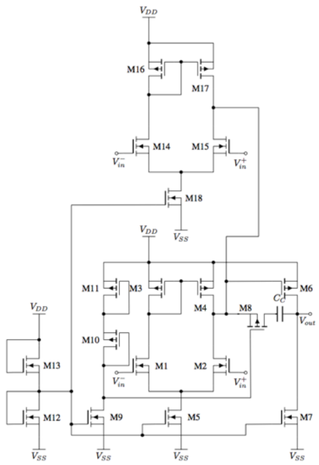

Fig. 2. Schematic diagram of the redundant Operational Amplifier design topology.

TABLE I. DIMENSIONS OF THE ORIGINAL OPAMP TRANSISTORS

Transistor	W/L
M1, M2 and M7	30
M3, M4 and M11	38.5
M5	10
M6	215
M8	7
M9	5
M10 and M13	1
M12	19

For the dimensions specified on I, the simulated performance is shown in II.

TABLE II. PERFORMANCE OF THE ORIGINAL OPAMP

Parameter	Value
Open-loop Gain	88.5 dB
Phase Margin	61.5º
Unit Gain Frequency	118 MHz
SR+	81 V/µs
SR-	75.5 V/µs
Offset Voltage	25µV

B. Redundant OpAmp project

Initially, the only modification made to achieve this redundant design is to duplicate the input stage, as shown in Fig.2. The transistors dimensions remained the same as the ones in Fig.1, with M14, M15, M16, M17 and M18 having the same dimensions as M1, M2, M3, M4 and M5, respectively. In this case, the phase margin drops to 29º, therefore, further modifications are required so as to make the phase adjustment. The compensation capacitor was changed to Cc=1.5pF. Furthermore, an adjustment on M8 was made in order to achieve a phase margin of 60º. The final dimensions of this redundant design are shown in III and the comparison of the performance of this initial redundant design and the original one is shown in IV.

TABLE III. FINAL DIMENSIONS OF THE REDUNDANT OPAMP TRANSISTORS

Transistor	W/L
M1, M2, M7, M14 and M15	30
M3, M4, M11, M16 and M17	38.5
M5 and M18	10
M6	215
M8	12
M9	5
M10 and M13	1
M12	19

TABLE IV. PERFORMANCE COMPARISON BETWEEN PRELIMINAR REDUNDANT OPAMP AND THE ORIGINAL OPAMP.

Parameter	Original	Redundant
Open-loop Gain	88.5dB	88.5 dB
Phase Margin	61.5º	61º
Unit Gain Frequency	118 MHz	128 MHz
SR+	81 V/µs	107.5 V/µs
SR-	75.5 V/µs	89.5 V/µs
Offset Voltage	25µV	25µV

As it can be seen in IV, the final redundant design presents a better performance for gain bandwidth and slew rate when no radiation is applied. In the next section, the analysis will be so as to analyze the variation of this response with the presence of radiation.

III. RADIATION SIMULATION

The strategy of using a redundant input stage is important for reducing the effects of radiation on the OpAmp. So as to analyze if the redundant input stage indeed enhances the device performance with radiation, it is necessary that the transistors parameters are varied so as to simulate the radiation effects. Currently, there is much information in literature about the effects of radiation on MOSFETs and the behavior of some parameters with dose, nevertheless, there is no precise and complete transistor modeling for a radiation analysis. Therefore, transistor response with dose is simulated by varying the main parameters that are affected by radiation: threshold voltage, mobility and leakage current. A second possibility is to build radiation libraries from radiation tests, i.e., the libraries parameters are based on the tests results. However, there is no available open-source ready-to-use simulation library that represents the transistor's parameters change with dose.

Therefore, it is necessary to estimate the transistors response by varying some transistor's parameters to see how the OpAmp's parameters shift. The simulations will occur in two different contexts: i) when all NMOS transistors are affected the same way and ii) when transistors are affected differently (mismatches). These two approaches were used because radiation can affect the system as whole or only some parts of it (and even only some specific transistors). Therefore, this analysis covers these different aspects of radiation effects on OpAmp. On both cases, three different parameter variations will be analyzed as shown in V.

TABLE V: SIMULATION ROUTINE FOR DETECTING THE OPAMP PERFORMANCE VARIATION FOR TRANSISTORS PARAMETERS VARIATIONS.

Variation	Parameter	Measurements
Transistors are affected equally	Threshold Voltage	DC Open Loop Gain Gain Bandwidth Offset Voltage Slew Rate
	Mobility	
	Drain-source current	
Transistors are affected differently	Threshold Voltage	
	Mobility	
	Drain-source current	

A. Simulations when all NMOS transistors are affected equally

Firstly, it was analyzed how each device operates when all the NMOS transistors in the circuit are equally affected by radiation. Usually, in integrated circuits, NMOS and PMOS transistors are, each, grouped separately. Therefore, a more uniform variation should be expected among all NMOS transistors of the device and, thus, this analysis is representative of the whole circuit. The following topics present the analysis of each one of the parameters that were varied according to V so as to analyze how radiation affects each of the systems. DC Open Loop Gain and Offset Voltage were simulated, but since redundant and traditional design presented the same response, the graphics were omitted here.

i. Threshold Voltage

The Threshold Voltage variation analysis was made by varying the level-7 Spice parameter VTH0 of each transistor. The selected range of values corresponds to a variation from (-50%) up to +150% of the nominal threshold voltage value. Fig. 3-4 show the graphic variation of the OpAmp parameters.

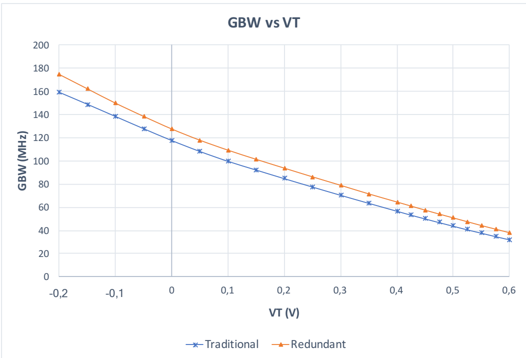

Fig. 3. Gain Bandwidth variation with a variation of VTH0 in NMOS.

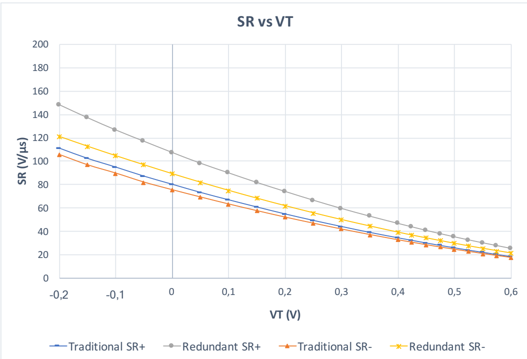

Fig. 4. Slew rate variation with a variation of VTH0 in all transistors.

In Fig. 3 and Fig.4, it is clear that throughout the whole range, the redundant design presents a better performance. Nevertheless, the radiation variation is roughly proportional. Therefore, it can be seen that the redundant topology and the traditional one presents a similar performance in terms of radiation hardening, when there is a threshold voltage deviation on the OpAmp NMOS transistors.

ii. Mobility

The Mobility variation analysis was made by varying the level-7 Spice parameter U0. The selected range of values corresponds to a variation of about 50% of the nominal mobility value. Fig. 5-6 show the graphic variation of the OpAmp parameters.

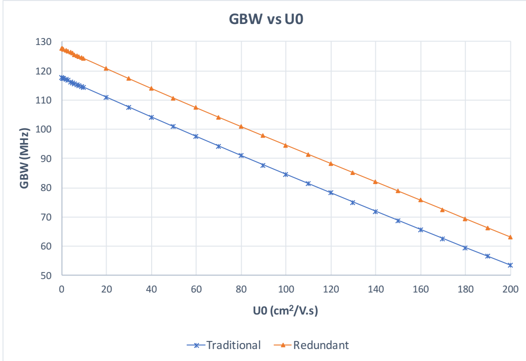

Fig. 5. Gain Bandwidth variation with a negative variation of U0 in NMOS.

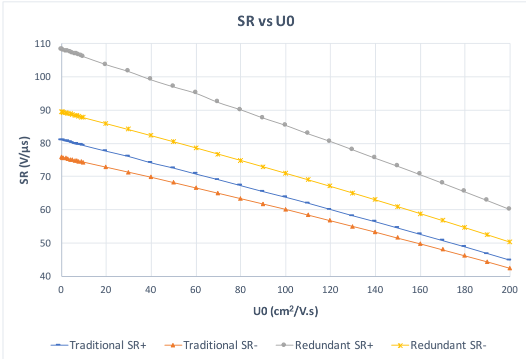

Fig. 6. Slew rate variation with a negative variation of U0 in NMOS.

In Fig. 5-6, it is clear that throughout the whole range, the redundant design presents a better performance. Therefore, it can be seen that the redundant topology and the traditional one presents a similar performance in terms of radiation hardening, when there is a mobility decrease on the OpAmp NMOS transistors.

iii. Drain current

The Drain current variation analysis was made by adding to each NMOS transistor of the system a parallel NMOS transistor whose gate-source voltage is controlled by an independent voltage source (called Vg). The selected range of selected voltage values roughly corresponds to a drain-source current range from 1nA to 100µA, which correspond to a variation of about 50% of the nominal drain-source current (this value varies according to each transistor). Fig. 7-8 show the graphic variation of these parameters.

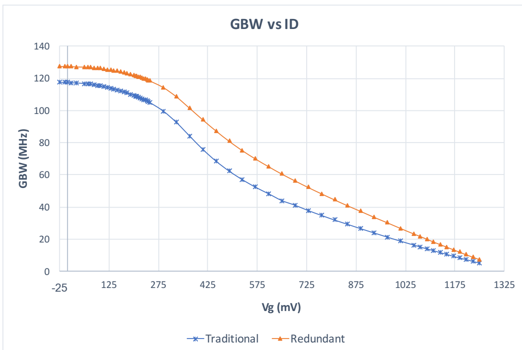

Fig. 7. Open loop gain variation with a variation of Vg in all transistors.

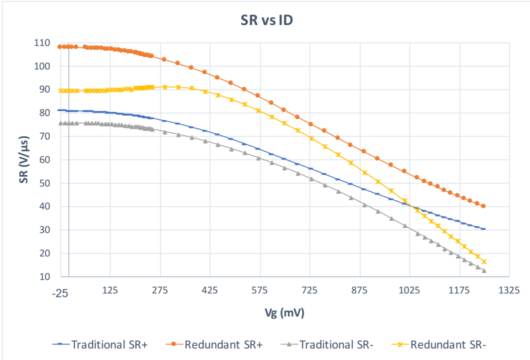

Fig. 8. Slew rate variation with a variation of Vg in all transistors.

In Fig. 7-8, it is clear that throughout the whole range, the redundant design presents a better performance. Nevertheless, the radiation variation is roughly proportional. Therefore, it can be seen that the redundant topology and the traditional one presents a similar performance in terms of radiation hardening, when there is an increase in the drain-source current on the OpAmp transistors.

B. Simulations when transistors are affected differently (mismatch)

When radiation affects differently one single transistor that is supposed to be matched with others, OpAmp parameters can be largely affected. The device gain (and therefore its gain bandwidth) and its offset voltage largely depends on how well transistors are matched, mainly the differential pair in the input stage. In this case, it was analyzed how the mismatch due to radiation effects affects both systems in order to compare them, with a focus on the differential pair. Since there are different combinations of transistors that can be affected, each one of these mismatch cases must be analyzed individually. Table VI shows all the possible mismatch cases and the terms and codes used in this work.

Each of the following topics present the analysis of each parameter that was varied (table V) so as to analyze how radiation affects each of the systems. Slew rate was also simulated, but since it did not vary much, the results were omitted here.

TABLE VI: MISMATCH CASES FOR EACH TOPOLOGY AND THE USED TERMINOLOGY.

Topology	Used Term	Code	Affected transistor(s)
Traditional	Traditional 1	T1	{M1} or {M2}
	Traditional 2	T2	{M1, M2}
Redundant	Redundant 1	R1	{M1}, {M2}, {M14} or {M15}
	Redundant 2 equal	R2e	{M1, M14} or {M2, M15}
	Redundant 2 opposite	R2o	{M1, M2}, {M1, M15}, {M2, M14} or {M14, M15}
	Redundant 3	R3	{M1, M2, M14}, {M1, M2, M15}, {M1, M14, M15}, {M2, M14, M15}
	Redundant 4	R4	{M1, M2, M14, M15}

i. Threshold Voltage

As in the previous situation, the Threshold Voltage variation analysis was made by varying the level-7 Spice parameter VTH0. The selected range of values corresponds to a variation of up to 22.5% of the nominal threshold voltage value. Fig. 9-11 show the graphic variation of some important OpAmp parameters.

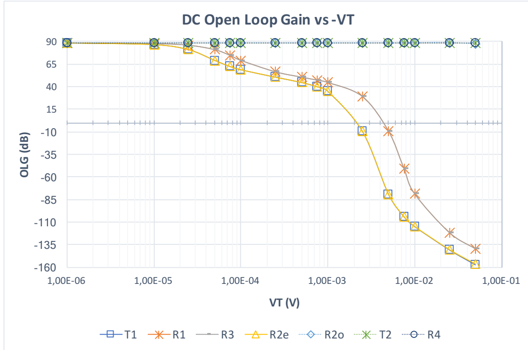

Fig. 9. DC Open loop gain variation with a negative variation of VTH0.

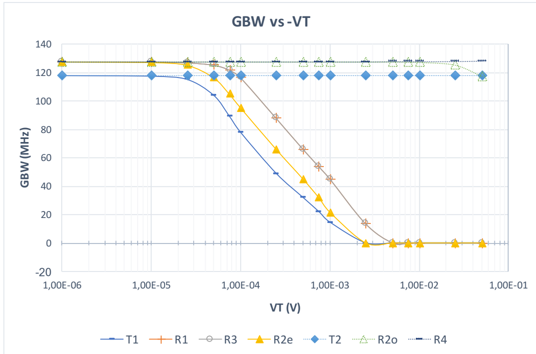

Fig. 10. Gain Bandwidth variation with a negative variation of VTH0.

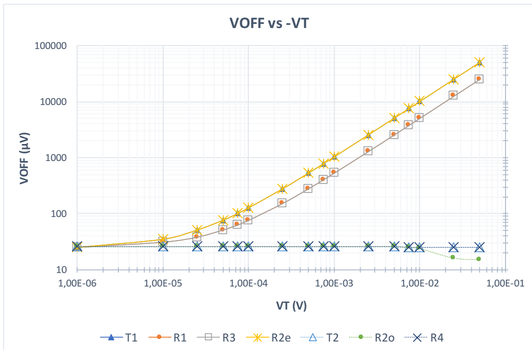

Fig. 11. Output offset voltage (absolute value) variation with a negative variation of VTH0.

Fig. 9-11 show that in the mismatch cases T2, R2o and R4, there is only a slight variation of the analyzed parameters. This occurs because of the symmetry of the failures, such that one error counterpoints the other. In Fig. 9 and 11, R2e and T1 have a similar behavior and so do R3 and R1. In Fig. 10, R2e is better than T1 and, even though T2 barely changes with dose, for lower variations, R2o and R4 are better than T2 . It can be seen that in all the three cases, R3 and R1 presents a better performance than R2e and T1; R4 and R2o has a better performance than all the others; T2 is better than R2e but its comparison with R2e and R3 depends on dose.

ii. Mobility

As in the previous situation, the Mobility variation analysis was made by varying the level-7 Spice parameter U0. The selected range of values corresponds to a variation of up to 25% of the nominal mobility value. Fig. 12-14 show the graphic variation on cases when the variation is more evident.

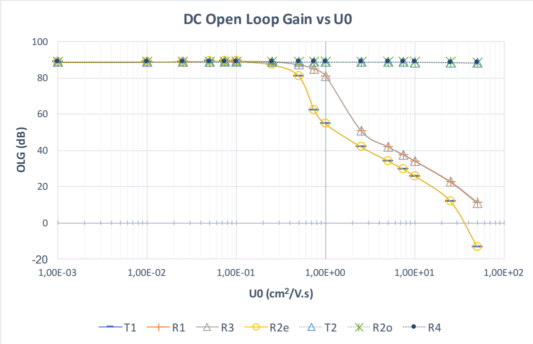

Fig. 12. DC Open loop gain variation with a negative variation of U0.

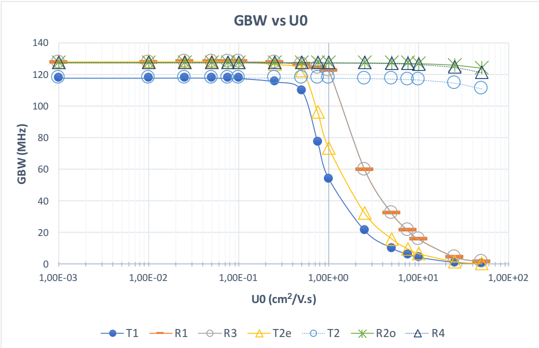

Fig. 13. Gain Bandwidth variation with a negative variation of U0.

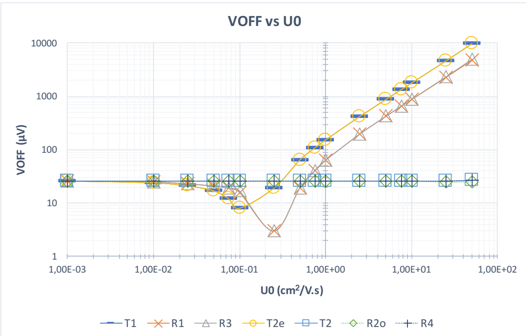

Fig. 14. Output offset voltage (absolute value) variation with a negative variation of U0.

Fig. 12-14 show that in the mismatch cases T2, R2o and R4, there is only a slight variation of the analyzed parameters. This occurs because of the symmetry of the failures, such that one error counterpoints the other. In Fig. 12 and 14, R2e and T1 have a similar behavior and so do R3 and R1. In Fig. 13, R2e is better than T1 and, even though T2 barely changes with dose, for lower variations, R2o and R4 are better than T2 . It can be seen that in all the three cases, R3 and R1 presents a better performance than R2e and T1; R4 and R2o has a better performance than all the others; T2 is better than R2e but its comparison with R2e and R3 depends on dose.

iii. Drain current

As in the previous situation, the Drain current variation analysis was made by adding a parallel NMOS transistor whose gate-source voltage is controlled by an independent voltage source (called Vg). The selected range of selected voltage values roughly corresponds to a drain-source current range from 1nA to 1µA, which correspond to a variation of about 0.5% of the nominal drain-source current (this value varies according to each transistor). Fig.15-17 show the graphic variation on cases when the variation is more evident.

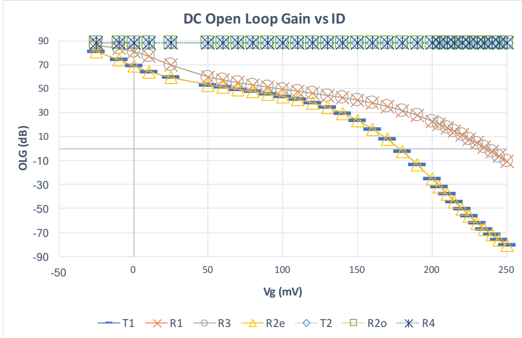

Fig. 15. DC Open loop gain variation with a negative variation of Vg.

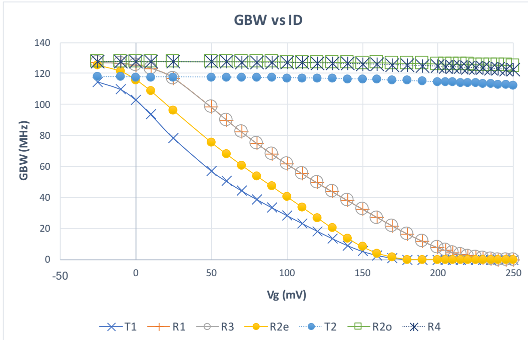

Fig. 16. Open loop gain variation with a negative variation of Vg.

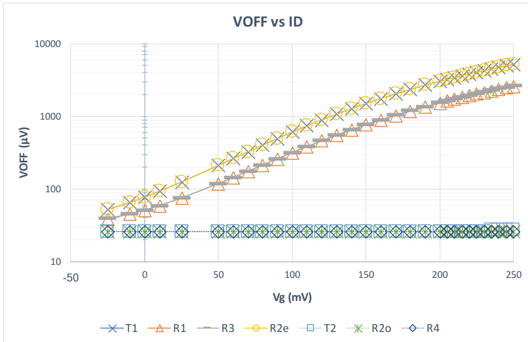

Fig. 17. Output offset voltage (absolute value) variation with a negative variation of Vg.

Fig. 15-17 show that in the mismatch cases T2, R2o and R4, there is only a slight variation of the analyzed parameters. This occurs because of the symmetry of the failures, such that one error counterpoints the other. In Fig. 15 and 17, R2e and T1 have a similar behavior and so do R3 and R1. In Fig. 16, R2e is better than T1 and, even though T2 barely changes with dose, for lower variations, R2o and R4 are better than T2 . It can be seen that in all the three cases, R3 and R1 presents a better performance than R2e and T1; R4 and R2o has a better performance than all the others; T2 is better than R2e but its comparison with R2e and R3 depends on dose.

IV. Analysis and Discussion

When the transistors of the system are affected equally (first case), it was noticed that the performance of the redundant OpAmp and the traditional one presented a similar performance in terms of radiation hardening. However, when specific transistors are affected this is not always true. Therefore, so as to make a proper analysis of it, it must be considered the mismatch cases when the redundant design is better and the ones when the traditional one is along with their probability of occurrence. A way to analyze it mathematically is proposed by (1).

$$v_{A,B} = \sum_a \sum_b P_a . P_b . \delta_{ab} \quad (1)$$

where $v_{A,B}$ is a value from 0 to 1 that represents if redundant design (A) is statistically better than the traditional one (B); δ_{ab} can assume the values according to each *ab* case 1 (if A is better than B), 0 (if B is better than A) or 0.5 (if this is comparison depends on dose); P_b represents the probability that a certain b mismatch case occurs in B and P_i the probability that a certain mismatch case a occurs in A, both as a function of p (which is the probability that a transistor is affected by radiation). $v_{B,A}$, then, would be the value that represents if the traditional design (B) is better than the redundant one (A). If $v_{A,B} > v_{B,A}$, the redundant design is statistically better than the traditional one. Table VII and VIII presents the values for each P and each δ, respectively.

TABLE VII: OCCURRENCE PROBABILITY OF EACH MISMATCH CASE.

Mismatch case	P_a or P_b
T0	$P_b = (1-p)^2$
T1	$P_b = p(1-p)$
T2	$P_b = p^2$
R0	$P_a = (1-p)^4$
R1	$P_a = 4.p.(1-p)^3$
R2e	$P_a = 2.p^2(1-p)^2$
R2o	$P_a = 4.p^2(1-p)^2$
R3	$P_a = 4.p^3(1-p)$
R4	$P_a = p^4$

T0 and R0 are the cases when no transistor is affected by radiation on traditional and redundant design, respectively.

TABLE VIII: PERFORMANCE COMPARISON ACCORDING TO THE MISMATCH CASES BASED ON SECTION III.

Mismatch cases (Redundant)	Mismatch cases (Traditional)	δ_{ab}	δ_{ba}
R2o, R4, R0	T0, T1, T2	1	0
R1, R3, R2e	T1	1	0
R1, R3, R2e	T0, T2	0	1
R2o, R4	T0, T2	0.5	0.5

Therefore:

$$\begin{aligned} v_{A,B} = {} & (1-p)^4.1 + 4.p.(1-p)^3.[2.p(1-p).1] \\ & + 4.p^2.(1-p)^2.[(1-p)^2.0.5 \\ & + 2.p.(1-p).1 + p^2.1] \\ & + 2.p^2.(1-p)^2.[2.p.(1-p).1] \\ & + 4.p^3.(1-p).[2.p.(1-p).1] \\ & + p^4.[(1-p)^2.0.5 \\ & + 2.p.(1-p).1 + p^2.1] \end{aligned} \quad (2)$$

$$v_{B,A} = (1-p)^2.[4.p.(1-p)^3.1 + 4.p^2.(1-p)^2.0.5 + 2.p^2.(1-p)^2.1 + 4.p^3.(1-p).1 + p^4.0.5] + p^2.[4.p.(1-p)^3 + 2.p^2.(1-p)^2.1 + 4.p^3.(1-p).1] \quad (3)$$

Fig. 18 shows the graphic with these functions plotted.

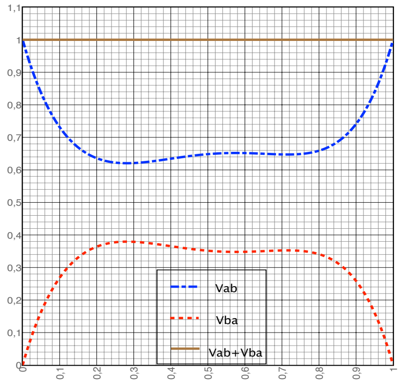

Fig. 18. Probability functions $v_{A,B}$ and $v_{B,A}$ as function of p.

From Fig. 18, it can be seen that statistically, regardless of the probability of a single transistor being affected by radiation (p), the redundant design presents a higher probability of being better than the traditional one. For lower probabilities (below 10%) this comparison is even favorable to the redundant design.

In this analysis, it was considered that all the parameters are equally relevant, but this would depend on each system. In that case, a different analysis could be held. However, the simulations show that on the analyzed parameters the redundant cell presents, indeed, a better radiation hardening performance than the traditional one.

V. CONCLUSION

In this work it was proposed a strategy for decreasing the radiation effects on a two-stages-Miller-compensated OpAmp. The strategy consisted of duplicating the input stage of the traditional OpAmp generating a redundant topology.

The traditional and the redundant circuits were designed in 0.35μm CMOS technology and simulated on LTSpice Software, considering three parameters variation (threshold voltage, mobility and drain-source leakage current) in two different cases: i) when all NMOS transistors of the device are affected equally and ii) when there is a mismatch among some NMOS transistors. After the analysis of these results, it was concluded that the redundant design presented a better performance than the traditional one, for the analyzed parameters were consistently better as they varied with dose.

REFERENCES

[1] P. E. Allen and D. R. Holberg, CMOS Analog Circuit Design, 2nd ed. New York: Orford University Press, 2002.

[2] T. C. Cavalcante, L. A. Faria, "Design and analysis of a two-stages Miller compensated OpAmp for high-speed applications", XVII SIGE, 2015.