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New Details about the Frequency Behaviour of Irradiated Bipolar Op Amps

F. J. Franco, Y. Zong and J. A. Agapito

***Abstract*— The frequency behaviour of irradiated bipolar op amps is always expected to worsen when the device is irradiated. In other words, parameters like the slew rate and the gain-bandwidth product are to decrease after either neutron or gamma tests. However, some neutron and TID tests performed on a large variety of bipolar op amps have shown that the evolution of the frequency behaviour is not as simple as it is usually believed. In fact, there is evidence of an increasing influence of the power supply values on the values of the former parameters, which can be extremely important in some devices. Also, the relationship among different frequency parameters has been investigated and, finally, an interesting scarcely reported phenomenon is depicted. This phenomenon is the appearance of spontaneous oscillations in fed-back op amps, without doubt related to a modification of the gain and phase margins of the devices.**

***Index Terms*— Bipolar technology, gain-bandwidth product, neutron irradiation, op amps, slew rate.**

I. Introduction

A WIDELY accepted fact is that the frequency behaviour of electronic devices worsens after being exposed to radiation [1]. This phenomenon is specially important in the case of bipolar operational amplifiers. Related papers have brought evidence that this happens either with ionisation or displacement damage [2]- [6]. However, the results of some neutrons tests performed by the Universidad Complutense de Madrid in the Portuguese Research Reactor (PRR) have shown that this phenomenon is more complex than what has been usually supposed.

The primary purpose of these neutron tests was to obtain information about the radiation tolerance of some commercial devices to be used in the cryogenic system of the LHC (CERN). A great deal of devices (not only op amps but also other devices like DACs, reference voltages, ASICs, etc.) were tested in the PRR since it mimics the predicted radiation environment in the LHC. Afterwards, if the device were still operative, their main DC & AC parameters were carefully measured to make a complete study of their evolution as the radiation value increases.

In the case of the op amps, we realised that the observed degradation was not different from that depicted in the literature (shift of offset voltage, increase of input bias currents, decrease of open loop gain, etc.) [1]. As expected, the main AC parameters of the bipolar op amps were not exceptions to this general behavior. However, we decided not only to measuring their values as a function of the radiation but we also investigated the relation among them, the influence of other parameters like the power supplies values, etc. Thus, we expected to progress in the knowledge of the effects of radiation on integrated devices as well as the discovery of hitherto unknown second-order phenomena.

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II. Test procedure

A set of low signal operational amplifiers were irradiated in a special facility at the Portuguese Research Reactor, placed in the Instituto Tecnológico e Nuclear of Portugal [7]. After five sessions of 12 h each, the neutron fluence in the centre cavity rises up to $5{\cdot}10^{13}$ n$\cdot$cm^{-2}, the background gamma radiation being between 1-3 kGy(Si). The energy spectrum of the neutron beam was similar to that of ^{235}U fission after removing the component of thermal neutrons. According to the calculations performed by the Portuguese Research Reactor staff, the damage factor is 1.28 [8]. In other words, all the neutron fluence values shown in this paper must be multiplied by this factor in order to express the fluence in 1-MeV n$\cdot$cm^{-2}.

Tested amplifiers were OP-07, OP-27 & OP-77, from Analog Devices, LF351, from Linear Technology, and OPA227, OPA277, OPA111, OPA602, OPA606, OPA627 & TLE2071, from Texas Instruments. Their characteristics can be found on manufacturers' websites [9]- [11]. During the irradiation, their leads were shorted, as standard tests suggest [12]. The devices received a neutron fluence between $0.38{\cdot}10^{13}$ n$\cdot$cm^{-2} and $9.8{\cdot}10^{13}$ n$\cdot$cm^{-2}, the vestigial gamma radiation dose being between 450 & 2700 Gy (Si). Neutron fluence values were measured with ^{58}Ni foils whereas total ionising dose was tracked with an ionisation chamber.

After checking that the devices were still functional once the irradiation ended, the values of the characteristic frequency parameters were measured with an AC accurate voltmeter (Keithley 2002) and a digital oscilloscope (Tektronik Tds3052B) according to a standard measurement protocol [13].

III. Frequency parameters associated to an op amp

The frequency behaviour of an operational amplifier is mainly determined by two important parameters: The gain-bandwidth product (also called unity-gain frequency, f_U) and the slew rate, *SR* [14]. The first parameter is related to the representation of the analog device in the Laplace's dominion and it is appropriate to describe the response to low amplitude input stimuli. On the contrary, the slew rate becomes important in the case of large amplitude signals since it determines the maximum response speed of the output signal. The reason is that the output voltage cannot change with a rate higher than *SR*, a typical consequence of this phenomenon being the transformation of a square wave input into a saw-shaped output signal.

A. Definition of the frequency parameters

In spite of the existence of several zeroes and poles, op amps are successfully described by means of the so-called "dominant pole model" [15]- [16]. According to this model, an op amp is just a differential amplifier with only one pole whose gain value depends on the frequency, *f*, as:

$$A(f) = \frac{A_0}{1 + j \cdot f/p_0} \quad (1)$$

where p_0 is the main pole of the op amp and A_0 the open loop gain. Usually, operational amplifiers work inside a fed-back network whose gain A_{DC} is set by external elements like resistors. According to feedback theory, whichever the close loop gain A_{DC} may be, the equality $A_{DC} \cdot f_{DC} = A_0 \cdot p_0$, with f_{DC} the bandwidth of the fed-back network, is always accomplished [17]. In other words, the product of the DC gain and the bandwidth is invariant for each sample. From now on, the value of this product will be symbolised as f_U.

On the other hand, the slew rate is the parameter that measures the highest change rate of the output voltage. In other words:

$$\left| \frac{\delta V_{OUT}}{\delta t} \right| \leq SR \quad (2)$$

This is the most popular definition of slew rate. However, it is better to use an alternate expression for a more accurate description of the slew rate phenomenon:

$$-SR_{NEG} \leq \frac{\delta V_{OUT}}{\delta t} \leq SR_{POS} \quad (3)$$

This new mathematical expression, highlighting the difference between the values of positive and negative slew rate, takes into account the asymmetry in the time response of the op amp and the different behaviour if the op amp output voltage is increasing or decreasing. In general, manufacturers' datasheets provide the lower of both values as the actual slew rate despite actual op amps having different response depending on the direction of the output voltage change.

B. Calculation of f_U and SR

Frequency parameters are directly related to the properties of the amplifier input stage [16]. Op amps usually consist in three stages (input, gain and output), always the input stage being a differential pair biased by a current source, I_Q. This differential pair can be made with either bipolar or field effect transistors. Besides, between the input and the output of the gain stage there is usually a compensation capacitor, C_X, with the purpose of giving stability to the op amp (fig. 1). Gain-bandwidth product and slew rate are related to the properties of these components. It is easily deduced that, in a first approximation, the gain-bandwidth product of any op amp is [15]:

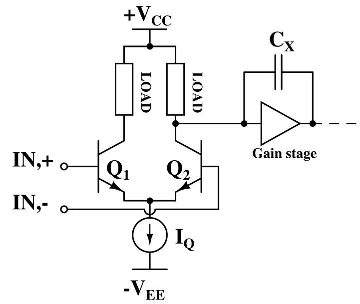

Fig. 1. Simplified structure of the input stage of a bipolar op amp.

$$f_U = \frac{G_M}{2 \cdot \pi \cdot C_X} \quad (4)$$

where G_M is the transconductance of the transistors of the differential pair. In case the pair is bipolar, the transconductance of the bipolar transistors is I_C/V_T [15], where I_C is the collector current. In a differential pair, this current is usually approximated to $I_C/2$ since the current source biasing the differential pair is distributed between both identical branches. In the case of bipolar input stages, the following results is finally obtained [15]:

$$f_U = \frac{I_Q}{4 \cdot \pi \cdot V_T \cdot C_X} \quad (5)$$

This expression is valid in most bipolar op amps with the few exceptions of those with a Darlington input transistor, where the dividing factor is 8 instead of 4, and those with an emitter resistor [18]. In the case of junction field transistors, the transconductance is:

$$G_M = 2 \cdot \sqrt{\frac{I_{DSS}}{V_P^2}} \cdot \sqrt{I_D} \quad (6)$$

where I_{DSS}, V_P and I_D are the saturation current with $V_{GS} = 0$, the pinch-off voltage and the drain-to-source current. After some steps, the following expression for the unity-gain frequency in JFET op amps is eventually deduced:

$$f_U^2 = \frac{I_{DSS}}{(\pi \cdot C_X \cdot V_P)^2} \cdot \frac{I_Q}{2} \quad (7)$$

Let us focus now on the value of the slew rate. The best way to calculate the slew rate value is to suppose that the compensation capacitor, C_X, is charged and discharged by the source current biasing the input stage. From this postulation, the following expression is easily obtained [16]:

$$SR = \frac{I_Q}{C_X} \quad (8)$$

This really simple expression is the most popular one to calculate the value of slew rate although it fails to predict the existence of two values of slew rate. Therefore, in order to skip these drawbacks, second-order phenomena will be added to the model in the following sections to explain the behaviour of irradiated op amps.

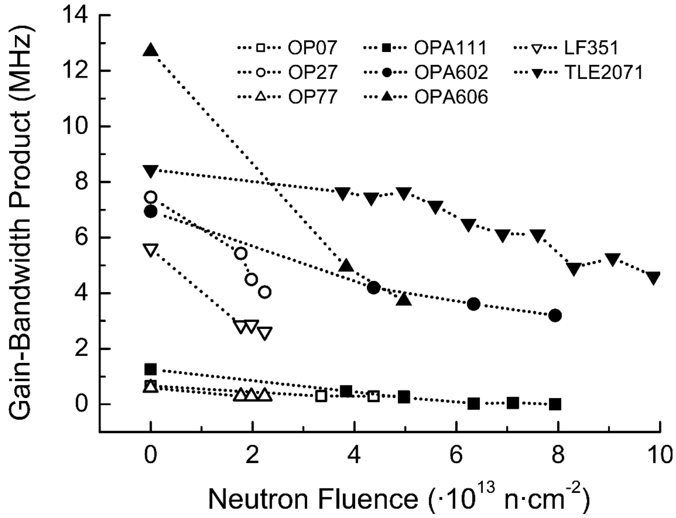

Fig. 2. Evolution of f_U in proportion to the neutron fluence.

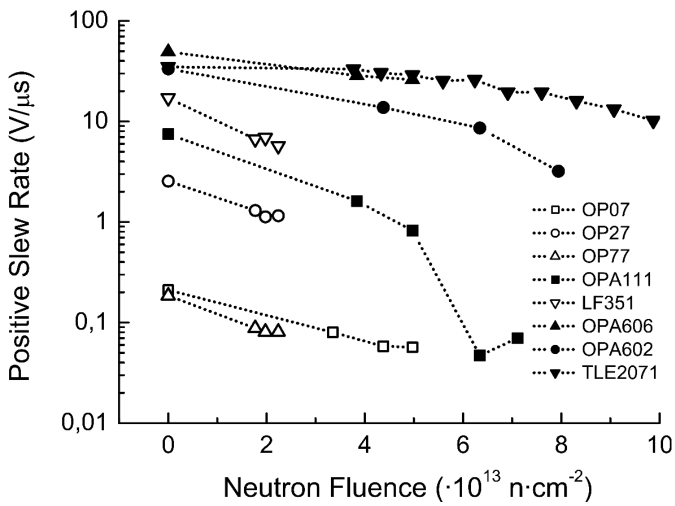

Fig. 3. Evolution of positive slew rate in proportion to the neutron fluence.

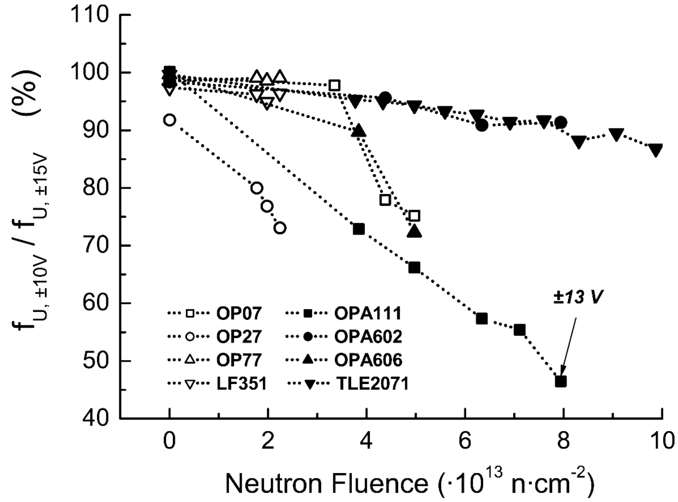

Fig. 4. Ratio between the values of f_U with power supplies of $\pm$10V and $\pm$15V as the neutron fluence increases. One sample of the OPA111 could not work with $\pm$10V so the values of f_U were measured with $\pm$15V & $\pm$13V, the minimum effective power supply value.

IV. Results

A. *Influence of power supplies*

The first phenomenon to be studied is the influence of the power supplies values on the frequency behaviour. As it was previously said, the frequency behaviour of the irradiated operational amplifiers worsens as the radiation damage increases. As expected, this fact is backed up by the experimental data (fig. 2 & 3), which show the evolution of the gain-bandwidth product and positive slew rate of the neutron-irradiated op amps, where a decrease in both parameters was found.

However, the evolutions of the op amps has a very interesting property. Fig. 4 proves that the gain-bandwidth product of irradiated op amps shows an increasing dependence on the power supplies values. In this graph, the values of $f_{U,\pm 10}/f_{U,\pm 15}$ for different types of amplifiers have been plotted as a function of the neutron fluence. In most of the op amps, not irradiated samples have a very small difference between both values so the value of $f_{U,\pm 10}/f_{U,\pm 15}$ is initially very close to 100% . The only exception is OP-27, where the ratio is about 90%. However, as the neutron fluence increases, the ratio value falls. The size of this decrease was found to be very dependent on the model. For instance, the gain-bandwidth products of OPA627 and OP-77 hardly show a dependence on the power supplies even in the most irradiated samples. On the contrary, this phenomenon becomes extremely important in other devices (OPA111, OPA606, OP-07), where an hypothetical decrease of the power supplies from $\pm$15V down to $\pm$10V yields a decrease of 30-50% in the value of f_U. Finally, a similar deppendence on the power supply value was found in the case of the slew rate.

B. *Relationship between the slew rate and f_U*

The second point to deal with was the relationship between the two main frequency parameters. Due to the fact that the frequency behaviour depends on the type of input stage, the set of op amps will be divided into two categories, regarding the bipolar or JFET nature of this stage.

1) Bipolar input stages: In the case of bipolar op amps, the relationship between *SR* and f_U is extremely simple. In fact, after operating with (5) and (8), the following expression comes up:

$$\frac{SR}{f_U} = 4{\cdot}\pi{\cdot}V_T \tag{9}$$

At room temperature, $V_T \simeq 0.026V$ so $SR \simeq 0.327 \cdot f_U$. This expression is valid for most of the bipolar op amps, except for some exceptions like, e. g., the op amps with Darlington pairs replacing the differential pair transistors. Table I shows the evolution of this coefficient in three models of bipolar devices with power supplies of $\pm$15 V (OPA227 & OPA277 have been removed because of another phenomenon that will be explained later). The most interesting fact is that the theoretical relationship is accomplished only by the not irradiated samples. On the contrary, the ratio between the parameters decreases in proportion to the neutron fluence. The most dramatical decrease happened in the case of the most irradiated sample of OP-07, where this ratio reached a value of 0.175, about a half the initial value of $4 \cdot \pi \cdot V_T$.

TABLE I
RATIO BETWEEN SLEW RATE AND f_U IN SOME IRRADIATED BIPOLAR OPERATIONAL AMPLIFIERS

Φ	f_U	$SRPos$	$SRNeg$	SRp/f_U	SRn/f_U
OP-07					
0	0.664	0.211	0.229	0.318	0.344
3.35	0.299	0.080	0.084	0.268	0.282
4.38	0.287	0.058	0.054	0.203	0.188
4.97	0.289	0.057	0.051	0.196	0.175
OP-27					
Φ	f_U	$SRPos$	$SRNeg$	SRp/f_U	SRn/f_U
0	7.20	250	2.40	0.347	0.330
1.77	5.92	1.26	1.60	0.213	0.270
1.98	5.44	1.11	1.46	0.204	0.268
2.24	5.29	1.10	1.23	0.208	0.233
OP-77					
Φ	f_U	$SRPos$	$SRNeg$	SRp/f_U	SRn/f_U
0	0.596	0.185	0.195	0.310	0.327
1.77	0.291	0.088	0.086	0.301	0.294
1.98	0.283	0.081	0.082	0.286	0.290
2.24	0.290	0.081	0.084	0.280	0.292
10^{13} n·cm^{-2}	MHz	V/μs	V/μs	V	V

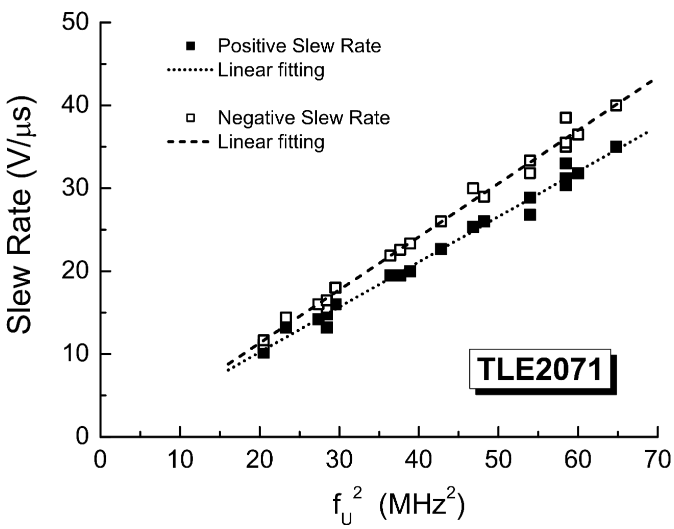

Fig. 5. Linear dependence of the values of *SR* and f_U^2 in the samples of TLE2071 at different values of neutron fluence.

2) JFET input stages: From (7)-(8), it can be easily shown that:

$$f_U^2 = K \cdot SR \tag{10}$$

$$K = \frac{2 \cdot \pi^2 \cdot C_X \cdot V_P^2}{I_{DSS}} \tag{11}$$

Therefore, there is a linear relationship between the square of the gain-bandwidth product and the slew rate. In fact, this relationship was found in most JFET input stage op amps, an interesting example being that of TLE2071, shown in fig. 5. As expected, all the symbols are distributed along a straight line. Eq. (10) seems to be true in most of the tested op amps although it fails in the case of the most irradiated samples, where the measured value of *SR* was smaller than that deduced from the extrapolation of the linear fitting of the least irradiated devices.

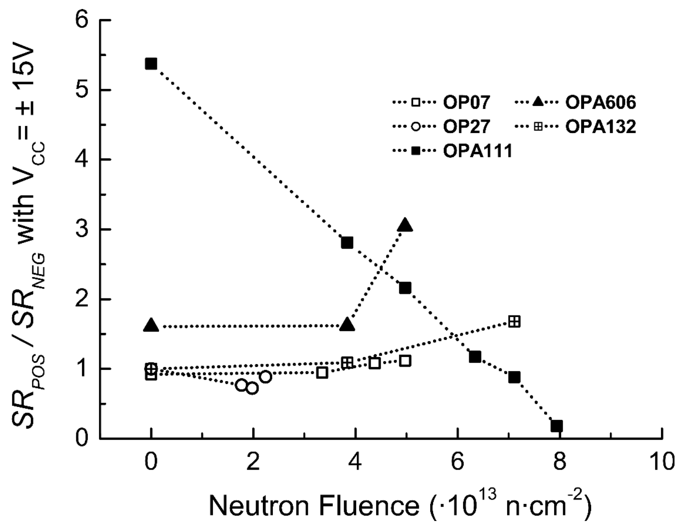

Fig. 6. Representation of SR_{POS}/SR_{NEG} measured in some devices with power supply values of ±15V.

C. Ratio between positive and negative slew rate values

Another interesting fact observed in a few irradiated devices was the modification of the ratio between the positive and negative slew rate. Before the irradiation, most of the operational amplifiers, with some exceptions like OPA606 & OPA111, had very close values of both parameters. In other words, the ratio between SR_{POS} and SR_{NEG} is close to 1 in these devices. However, as the neutron fluence increases, the ratio changes in some of the devices, as fig. 6 shows. Most of the devices are not included in the graph since they did not undergo any modification during the irradiation. On the contrary, this phenomenon is really significant in some types of amplifiers, like the OPA111.

D. Spontaneous oscillations

In some devices (OPA227 & OPA27), another phenomenon different from the typical decrase of f_U and SR was found: an oscillating signal in the output. Fig. 7 shows the output voltage measured with a digital oscilloscope of an OPA277 sample while it was biased as a buffer and with grounded input. In other words, inverting input and output were shorted and non-inverting input was connected to ground. It must be emphasised the fact that neither capacitors nor inductors loaded the sample so the oscillation appeared as a consequence of the degradation of the op amp. The shape of the output signal is very distorted and, hence, cannot be studied as a sinusoidal signal. Therefore, it will be described by means of the period and the r.m.s. voltage value (fig. 8-9). In both devices, the oscillations seems to have the following characteristics:

- There is a minimum neutron fluence value necessary so that oscillations may appear. E. g., in the case of OPA277, this threshold value is between 2.2-2.40·10^{13} n·cm^{-2}.
- The oscillation period increases in proportion to the neutron fluence.
- R.M.S voltage increases with neutron fluence until reaching a top value. Larger neutron fluences values make the

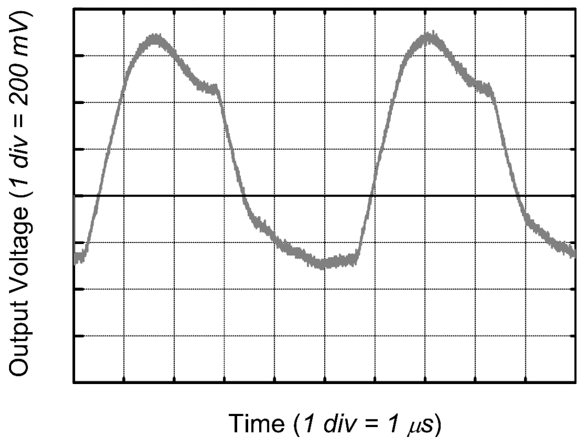

Fig. 7. Output voltage of an irradiated OPA277 when it was biased as a buffer with grounded input (Neut. fluence = $5{\cdot}10^{13}$ n$\cdot$cm^{-2}).

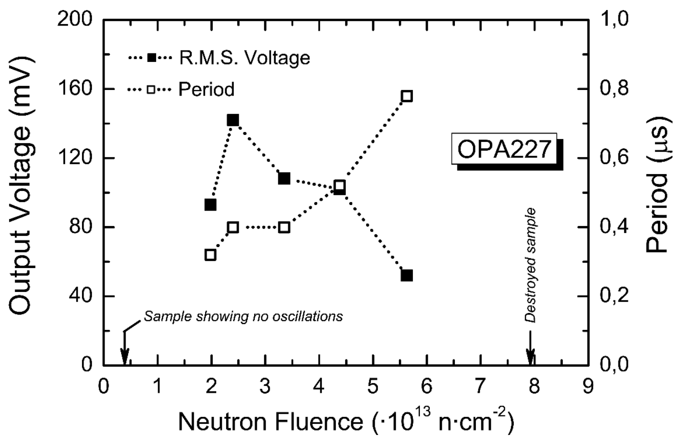

Fig. 8. Characteristics of the oscillations observed in OPA227. Black squares are related ot the sized of the output signal while the white ones show the evolution of its period. Arrows above the X-axis refer either samples not showing oscillations or those not able to work.

output voltage decrease.

Finally, oscillating signals can be modified or even removed by means of external capacitors. This is extremely important since this is the typical behaviour of unstable systems, where the phase and gain margins have become negative, indication of a shift of the internal poles and zeroes towards lower frequency values.

E. TID tests

In order to determine the influence of the ionizing radiation in the experimental results, an accelerated ^{60}Co test on the op amps was performed up to 18 kGy(Si), irradiation that also took 60 hours. This TID value was 5 to 10 times higher than the dose measured in the neutron facility and was chosen to investigate the TID tolerance of the devices for a later use in the LHC cryo- genic instrumentation. The results obtained from this test can be used to discriminate the influence of the TID on the evolution of the amplifiers although the application of these results is not immediate since the dose rate is increased as well. In fact, there is a lot of works that demonstrate that the damage caused by TID in typical op amp

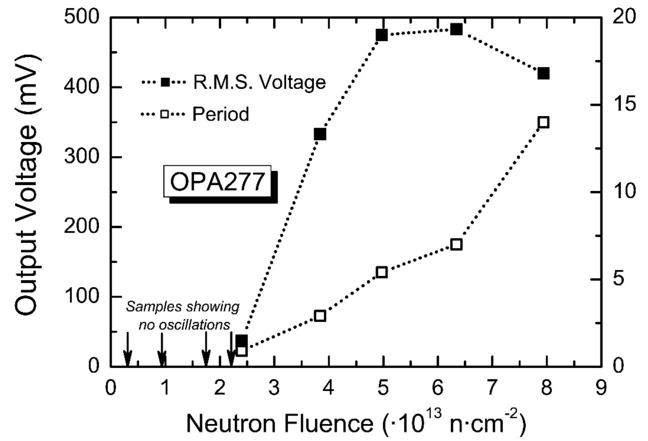

Fig. 9. Characteristics of the oscillations observed in OPA277. The four arrows above the X-axis show the neutron fluence that was received by the samples in which oscillations were not observed.

parameters may be 10-20 times larger in low dose rate tests than in accelerated ones [19], [20]. However, another paper reports that the slew rate of a typical op amp, the LM124, is not very sensitive to the enhanced low dose rate ef- fect [21]; e.g., at a TID value of 1 kGy(Si), V_{OS}, I_B & I_{OS} showed an enhanced damage factor on the order of 10-20 from high to ultra-low dose rate whereas in the case of slew rate the enhanced damage factor was only 2-3.

In order to determine the influence of the ionising radiation in the experimental results, an accelerated ^{60}Co test on the operational amplifiers was performed up to 18 kGy(Si). ATLAS test procedure indicates that results from accelerated tests can be similar to low dose rate tests with a TID value 5 times lower [12] so the results obtained in this test are comparable to those of a test of 3.6 kGy(Si), whichever the dose rate may be. In any case, this TID value is higher than the maximum value reached in the neutron facility (2.7 kGy (Si)).

The main results of this test are the following:

- All the irradiated amplifiers underwent a decrease in the gain-bandwidth product and slew rate value. However, by no menas this degradation was as significant as that observed in the samples irradiated in the neutron facility. E.g., an OPA111 exposed to TID showed a decrease in f_U from 1.3 Mhz down to 1.1 Mhz while this decrease was down to only 31 kHz in another sample that received $6.34{\cdot}10^{13}$ n$\cdot$cm^{-2} & 2.4 kGy(Si).
- The influence of power supplies values in the frequency parameters has not been modified at all. In fact, the values of $f_{U,\pm 10V}/f_{U,\pm 15V}$ before and after the irradiation are similar.
- In bipolar op amps, the ratio between *SR* and f_U is 0.32-0.34 V after the irradiation.
- No oscillations were observed.

In short, the only significant fact is the worsening of frequency behaviour. However, none of the other phenomena observed after the neutron test was found after the ^{60}Co irradiation. Therefore, most of the experimental results reported in previous sections must have been caused by displacement damage instead of by ionisation. This conclusion is extremely

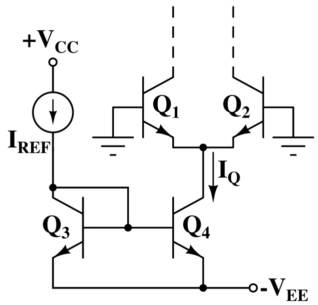

Fig. 10. Typical structure of bipolar input stage with a simple current mirror biasing the differential pair.

important since it will be the start point of a theory that explains the phenomena reported in the neutron irradiation.

V. Discussion

The main reason of the worsening of the frequency behaviour is the degradation of whether the internal transistors and the internal current sources and mirrors [1]- [2]. For example, let us study the structure of fig. 10, obtained from fig. 1 after replacing the ideal current source by an actual one consisting in a reference current source and a mirror, as it happens in most of commercial op amps [15], [22]. For simplicity, it is assumed that inputs are connected to ground and that all the transistors have the same gain, h_{FE}. In this case, the current biasing the input stage is:

$$I_Q = \frac{h_{FE}}{h_{FE}+2} \cdot I_{REF} \quad (12)$$

Therefore, I_Q depends on the value of h_{FE}, becoming 0 if h_{FE} does, and this is what actually happens in irradiated bipolar transisors. According to (5)-(8), the frequency parameters are proportional to either I_Q or $I_Q^{1/2}$, so the decrease of these parameters after gamma or neutron irradiation is immediately explained from the degradation of h_{FE}.

This decrease can be intensified due to two reasons. First of all, I_{REF} can also be affected by the radiation, leading to a lower value of I_Q. Moreover, the decrease of the gain-bandwidth product in bipolar op amps is even more important given that the collector currents, parameter that the transconductance, G_M, depends on, were assumed to be equal to the emitter current. This identification can be done in pristine transistors, where the current gain is very high but, on the contrary, it should not be accepted in irradiated bipolar transistors. In fact, $I_C/I_E = h_{FE}/(h_{FE}+1)$ so (12) should be multiplied by this factor to take this fact into account. In conclusion, the dependence of I_Q (and, hence, of f_U and *SR*) on h_{FE} becomes even more important than that predicted from (12), making the influence of the degradation of h_{FE} more significant.

A. Increasing influence of power supply values

The previous study succeeds in explaining the reason of the decrease of f_U and *SR* when the op amp is irradiated with either neutron or gamma radiation. Nevertheless, it fails at explaining the differences found between both kinds of irradiation. Therefore, the reason of this discrepancy are those phenomena that neutron radiation causes but that TID does not, like the carrier removal and the resistivity growth [23].

One of the main failures of the previous statement is that bipolar transistors have been too simply described. In fact, a typical phenomenon observed in actual transistors, the Early effect [24], has not been taken into account. A more accurate calculation of I_Q needs to multiply (12) by $(1 + (V_{EE} - V_{BE,Q1})/V_{EAR,Q1})$ to include the Early effect in Q_4. Therefore, the value of I_Q and, in consequence, those of f_U and *SR* are related to the power supply values. It is easily deduced that the higher the value of V_{EAR}, the less significant the influence of the power supply values. According to Sze [25], the Early voltage of a bipolar transistor can be calculated with the following expression:

$$V_{EAR} = \frac{q \cdot N_B \cdot W_B^2}{2 \cdot \epsilon_{Si}} \quad (13)$$

Most of the variables of this expression are technological or physical parameters (q, ϵ_{Si}, the electron charge and silicon dielectric constant, and W_B, the transistor base width). The last parameter is N_B, which is the base doping concentration, and this parameter is liable to change during the neutron irradiation. For instance, let us suppose that a PNP transistor has received a neutron fluence of 10^{14} 1-MeV n·cm^{-2}. The carrier removal, ruled by some exponential expressions (p. 242 in [1]), yields that the Early voltage value would decrease down to 48%, 88% and 98% of the initial value if the base doping concentration were, respectively, 10^{15}, 10^{16} and 10^{17} cm^{-3}. These are the typical base doping concentration in integrated transistors and such decreases in the value of V_{EAR} are large enough to explain the growing influence of the power supplies.

Obviously, commercial op amps have much more complex structures than that used in this theoretical approximation but, in any case, the dependence on the Early voltage is present. To support this idea, some opamps (uA741, LF351, LH0042 & LH0062), whose internal structure is found in the literature [15]- [18], were simulated in SPICE after modifying the parameters of the internal transistors. In these simulations, the diminution of the gain transistors, the increase of backward saturation current of PN junctions, etc. led to a diminution of the slew rate and gain-bandwidth product value. However, the only factor whose diminution causes an increasing influence of power supplies was, as expected, the Early voltage value.

Finally, it is interesting to underline the increasing influence of the power supplies on many characteristic parameters of irradiated devices. The most studied parameter is by large the input offset voltage, V_{OS}. Indeed, there is a specific parameter, the PSRR [14], that links V_{OS} and $\pm V_{CC}$ and a great deal of data about this parameter can be found on public databases [26]. However, the experimental results reported in this paper along with some others found in the literature [27] demonstrate that a lot of the main op amps characteristics may be dependent on the power supply values after suffering radiation damage and not only the PSRR value, as it is usually believed.

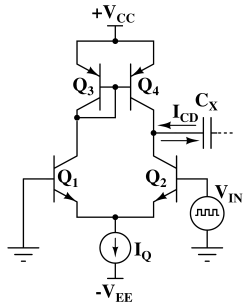

Fig. 11. Typical situation to calculate the slew rate.

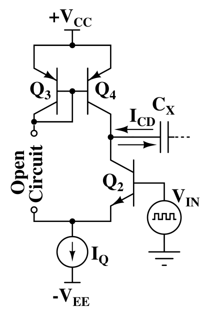

Fig. 12. Input stage with ideal cut-off transistors.

B. The evolution of slew rate

The evolution of JFET input stage op amps was successfully explained by (10). On the contrary, bipolar op amps have shown a strange behaviour in the evolution of slew rate that cannot be explained by the model of fig. 1. Like in the previous section, it is necessary to modify the simple op amp model to explain this phenomenon.

The most popular way to calculate the slew rate is to suppose that the op amp is just a differential amplifier and that one input is connected to ground while a square wave voltage source is applied to the other input (fig. 11). It is easy to understand that in case the wave amplitude switches between $\pm V_M$, with V_M larger than the typical voltage drop in a forward biased PN junction, one of the transistors of the differential pair is driven to cut-off state. In this situation, this transistor can be modelled as an open circuit. E.g., if $V_{IN} \gg 0$, Q_1 is cut off so fig. 11 becomes fig. 12. From this structure, it is easy to demonstrate that the current that drains C_X, I_{CD}, is equal to I_Q. Finally, since $I_{CD} = C_X \cdot (dV_X/dt)$ and $V_X \cong V_{OUT}$, (8) is immediately deduced.

The main problem of this model is that irradiated bipolar op amps in cut-off state should not be modelled as open circuits. In fact, it is much more realistic to describe the bipolar transistor as a couple of reverse-biased PN junctions (Collector-base, Emitter-base) with leakage currents (fig. 13). These currents are usually negligible but, in the case of irradiated bipolar transistors, large leakage currents are to be expected [1].

First of all, let us assume that the current gain of the bipolar transistors has decreased but it is much higher than 1. Thus, the currents flowing through the branches of the mirrors are alike and an inspection of fig. 13 would lead to the following

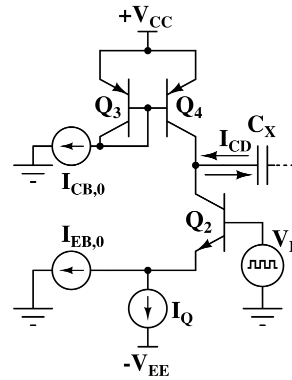

Fig. 13. Similar to fig. 12, but adding up leakage current sources.

result:

$$I_{CD} \simeq I_Q - (I_{CB,0} - I_{EB,0}) \tag{14}$$

Using this value instead of I_Q in (8) and dividing by (5):

$$\frac{SR}{f_U} \simeq 4 \cdot \pi \cdot V_T \cdot \left(1 - \frac{I_{CB,0} - I_{EB,0}}{I_Q}\right) \tag{15}$$

The following step is to estimate the size of $I_{CB,0}$ and $I_{EB,0}$. Assuming that these currents are similar to the reverse-bias generation current, as it usually happens [25], their values are proportional to τ^{-1} and to *W*, where τ is the minority carrier lifetime and *W* the depletion zone width [24]. Besides, in an asymmetric PN junction, *W* is proportional to $N_X^{-1/2}$, N_X being the impurity concentration in the less doped zone. Usually, $N_C \ll N_B$ and, assuming that the area of both junctions are similar, the leakage currents must be much more significant in the CB PN junction due to the multiplication by $N_C^{-1/2} \gg N_B^{-1/2}$. In conclusion, $I_{CB,0} \gg I_{EB,0}$ so $I_{CB,0} - I_{EB,0}$ is positive and increases with the neutron fluence. Moreover, the diminution of I_Q increases the influence of the leakage currents since it is dividing $I_{CB,0}$ in (15).

In consequence, the factor multiplying $4 \cdot \pi \cdot V_T$ in (15) diverges from 1 as the value of the neutron fluence grows. In the case of the samples exposed to gamma radiation, this decrease was not found. Two assumptions could explain this fact: First, the predicted increase of $I_{CB,0}$ and $I_{EB,0}$ could have been much smaller than that found after neutron irradiation. However, an more realistic alternative is that the currents balance each other. Unlike the displacement damage, the increase of $I_{CB,0}$ and $I_{EB,0}$ is related to the presence of leakage currents under the epitaxial oxide [1], not depending on the doping concentration,so they must have similar values.

Do leakage currents affect JFET op amps? A simple statement clears up this question: One of the main disadvantages of bipolar input stages is the high value of input bias currents, I_B. To minimise it, op amp designers make the value of $I_{Q,IN}$ as less as possible [16]. E.g., a value of I_B in the order of 1 nA can be only achieved if $I_{Q,IN}$ is of several microamperes. Therefore, accepting that the leakage currents are in the order of the input bias current (about 1 μA in the irradiated bipolar samples), we can conclude that $I_{CB,0}$ is likely to be in the same order as $I_{Q,IN}$. On the contrary, JFET input op amps do not suffer from the drawback of too high leakage currents so the value of $I_{Q,IN}$ is usually much larger than that found in bipolar input stages [16]. Therefore, the growth of leakage currents through the JFET gate may happen without consequence due to the large value of $I_{Q,IN}$. However, the presence of leakage currents could be an explanation of the degradation of slew rate value observed in very irradiated JFET op amps, usually larger than that predicted from the equation $SR = Kf_U^2$.

Finally, the difference observed between the evolution of positive and negative slew rate values could be attributed to second-order phenomena, as the degradation of mirror currents, that would introduce little differences between the current charging or draining the charge of C_X. However, this theory does not explain the case of the OPA111, where a large difference between both values was observed before the irradiation. This must be attributed to internal asymmetries, which were modified during the irradiation, leading to the results shown in fig. 6. Only a deep knowledge of their internal structure could help to explain the behaviour of these devices.

C. Slew rate vs. gain-bandwidth product

Analysing the experimental results, one may wonder which parameter is the most appropriate to study the degradation of the frequency behaviour. In our opinion, the radiation always causes a larger degradation in slew rate than in unity-gain frequency. This statement is based on two facts: First, the appearance of leakage currents in bipolar stages makes the value of SR/f_U decrease. Therefore, a decrease of f_U to a half of the initial value does not imply a similar diminution of the slew rate, but larger due to the decrease of the theoretical factor $4 \cdot \pi \cdot V_T$. An equivalent result comes from the proportionality between *SR* and f_U^2 in JFET input op amps. E.g, a decrease of f_U down to 10% of the initial value yields a decrease of *SR* down to only 1% of the initial value to keep SR/f_U^2 constant.

D. Origin of spontaneous oscillations

Finally, the appearance of oscillations in the output of the op amp in spite of the total absence of external devices points out to the fact that the op amp has become unstable. In other words, the phase margin has moved beyond 0^o. According to the feedback theory [17], oscillations only appear when the open loop gain at the frequency with a phase of 180^o is above 1. To accomplish these conditions, there must be at least three poles and a very high DC gain, as OPA227 & OPA277 have. The main pole of an op amp is set by the presence of C_X although there are actually others because of the internal capacitors of the transistors [16], the value of these poles and zeroes being dependent on the characteristics of the transistors, the bias currents, etc. Therefore, the degradation of the internal components of the op amp may pull the poles towards lower frequency values and make oscillations possible because of positive feedback.

Spontaneous oscillation in irradiated op amps has been reported by other authors [22] but, unlike the data presented in this paper, it appeared in regulators whose core was an op amp. In this case, the oscillations could have appeared due to a hypothetical instability of the op amp although it is also possible that the origin of the oscillations be the degradation of the feedback network.

VI. Conclusion

The frequency behavior of op amps worsens when the op amp is irradiated because of the decrease of the values of the gain-bandwidth product and the slew rate. However, the degradation of the op amp frequency behavior is not as simple as it is usually supposed. First of all, the influence of the power supplies becomes more important in amplifiers that suffered displacement damage, leading this fact to significant effects on some devices, where a decrease from ± 15 V to ± 10 V reduces the unity-gain frequency to a half of the initial value. Besides, it has been reported that the degradation of the slew rate is greater than that expected in the gain-bandwidth product. This phenomenon was observed in all the irradiated samples and could be explained by means of theoretical arguments related to the kind of input stage. In consequence, slew rate is the most appropriated parameter to study the degradation of the frequency behavior of bipolar op amps. Finally, the appearance of positive feedback caused by the shift of secondary poles of the op amps will cause in some models the appearance of a periodic output voltage after crossing a critical threshold radiation dose. In order to prevent this handicap, if an op amp is supposed to suffer displacement damage, the addition of external components to increase the phase margin is encouraged.

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