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GAMMA RAY EFFECT ON OP-AMP 741 AND TIMER 555 IC

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Abstract: The commercial used the 555 single timer and the 741 operational amplifiers (op-amp) were investigated under the gamma-ray radiation of the Co-60 source. The maximum total doses were used 2 kGy and 4 kGy to irradiate. The abnormal behavior in the 555 single timer circuit frequency was observed, which decreased from 202 to 195 Hz at 744 Gy gamma-ray radiations. In the results of 741 op-amp circuit, the amplitude signal of the 741 op-amp shows a maximum value of -0.054 dB at 4 kGy gamma dose and its slew rate decreases from 4 to 0.65 V/µs. The 555 single timer has two *pn* junctions and these cause that the 555 single timer is easily affected by the gamma radiation. Consequently, the integrated circuits must be tested to determine their resistance limits in the radiation environments.

Keywords: Gamma Ray, Op-Amp 741, Timer 555 IC, Semiconducting Junctions

OP-AMP 741 VE ZAMANLAYICI 555 IC ÜZERİNDE GAMA IŞINI ETKİSİ

Öz: Ticari olarak kullanılan 555 tekli zamanlayıcı ve 741 işlemsel yükselteç (op-amp), Co-60 kaynağının gama ışını radyasyonu altında incelenmiştir. Işınlama için maksimum toplam dozlar 2 kGy ve 4 kGy kullanılmıştır. 744 Gy gama ışını radyasyonlarında 202 Hz'den 195 Hz'e düşen 555 tekli zamanlayıcı devre frekansında anormal davranış gözlemlenmiştir. 741 op-amp devresinin sonuçlarında, 741 op-amp'in genlik sinyali 4 kGy gama dozunda maksimum -0,054 dB değerini göstermektedir ve yükselme eğimi 4'ten 0,65 V/µs'ye düşmüştür. 555 tekli zamanlayıcının iki *pn* bağlantısı vardır ve bu diyotlar 555 tekli zamanlayıcının gama radyasyonundan kolayca etkilenmesine neden olmaktadır. Sonuç olarak, entegre devrelerin radyasyon ortamlarındaki direnç sınırlarının belirlenmesi için test edilmesi gerekmektedir.

Anahtar Kelimeler: Gama Işını, Op-Amp 741, Zamanlayıcı 555 IC, Yarı İletken Bağlantılar

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1. INTRODUCTION

The technology is becoming widely used in integrated circuit chips for the advantages it can offer in specific applications (Dvornikov et al., 2017; Dvornikov et al., 2018). One of the important categories in the integrated chips are operational-amplifiers (op-amp) (Abel et al., 2021). The op-amps are used in many electronic circuits such as analog computers, amplifiers, oscillators, wave-shapers, regulators, rectification, signal analysis and generators, test and measurement systems, filter actions operations and sensors (Terrell, 1996; Um et al., 2020; Ferikoğlu and Topal, 2010). Hence, there are many usage areas from the personal computer to space technology. Besides performing the operational functions in the integrated circuits, it is expected that good performance in harsh environments such as simpler signal multiplexing, improves system performance, and avoids or minimizes signal degradation. (Elbuluk et al., 2009). The ideal op-amp is usually considered to have the following properties; infinite open-loop gain and input impedance R_{in}, and so zero input current, zero input offset voltage, infinite voltage range available at the output, infinite bandwidth with zero phase shift and infinite slew rate, zero output impedance R_{out}, infinite common-mode rejection ratio, infinite power supply rejection ratio (Roberge, 1975; Ashry et al., 2008; Gray et al., 2009).

The long lifetime and efficiency of the op-amps can be affected by external factors such as harsh environment, environmental radiation, so on. Especially, in the environments with high levels of radiation such as electromagnetic field, ionizing radiation can knock thousands of electrons loose, causing electronic noise and signal spikes. Although it is a problem that can have simple solutions for simple electronic devices, this is a particularly severe problem in the design of satellites, spacecraft, nuclear power stations, radiation oncology and physics laboratory which include the essential and the expensive technological devices. To protect the integrated systems from the environmental radiation, the integrated circuits and the sensors require high radiation resistance. For this reason, new components for the integrated circuits must be developed and the radiation effect on the op-amp components is required to investigate. Two fundamental damage mechanisms, lattice displacements (change of arrangement atoms, increasing in recombination centers) and ionization effects (transient, creating glitches and soft errors) take place in the electronic circuits because of radiation effect. Especially, the op-amps have been used mostly in nuclear applications, and therefore, these properties of it have to be characterized under ionizing radiation. It is well-known that the gamma particle has massless and high energy (average 1.25 MeV) thus, the gamma radiation is better than other ionizing radiation. The 555 single timer and op-amps 741 chips are vital components of most of these applications. Depending on the radiation, these components are a high probability of corruption. Therefore, these chips must be tested in a radiation environment to find the radiation hardening and so their characteristics are needed to define as a function of radiation dose (Schrimpf and Fleetwood, 2004; Baczuk, 1994; Soliman, 1993).

It is well known that the internal structure of the 555 single timer and op-amp 741 chips can be affected by the gamma radiation, which is a generated electron-hole pair by irradiation energy and applied bias in the internal transistors and diode. One of these components are bipolar junction transistor (BJT) and ionizing radiation degradation is generally caused by excess charge trapped on near the surfaces of their insulating layers and interfaces. Thus, the generated holes drift toward the anode, and the electrons drift toward the cathode in the influence of the internal electric field (Assaf, 2020; Babcock et al., 1995; Walldén, 2014; Claro and Santos, 2009). This effect reduces the minority carrier lifetime and so decreases its performance (Pien et al., 2010). The radiation-induced deterioration of BJT is largely due to two operations: a rise in the net positive charge trapped in the oxide covering the device, and an increase of traps positioned near the Si-SiO_2 interface, with energy levels approaching mid-gap (Baliga, 2010; Montagner et al., 1998). Ahn et al. investigated the effect of gamma radiation on the pnp Si BJTs. They were exposed with a total of 700 Gy radiation. They found that the gamma radiation enhanced the base current while decreasing the base-collector current amplification ratio since the gamma radiation causes enhanced recombination in the base region (Ahn et al., 2018).

In the present study, we firstly tested the resistances and the capacitors under the gamma radiation of Co-60 source with 4 kGy total dose and it is not observed any change in their signals. Also, the signal generator, power supply, and oscilloscope were used in the non-radiation environment and, the 555 single timer and the op-amp 741 were only tested under gamma radiation at room temperature. The obtained experimental results were presented to be initial information and waveform pre-radiation, and after exposed to gamma radiation. Additionally, the waveform output was tested and presented the limit of radiation hardness of the chips. In the integrated circuit with the 555 single timer, a drop in the frequency of the astable multivibrator was observed from 202 to 195 Hz at the gamma radiation in the range of 700-750 Gy, and then a linear decrease occurred until 194 Hz due to the increased dose. For frequency analysis, the loss is about 3.5 % in the 555 timer circuit. In the 741 op-amp, the amplitude of both input and output signal decreases due to the radiation, and here, the loss of output amplitude was calculated about 2.3 % when the radiation dose was 4 kGy. Consequently, the radiation causes corruption in the signal of the op-amps and therefore, their efficiency is directly affected.

2. EXPERIMENTAL DETAILS

The op-amp 741 is a high gain amplifier, which provides a low input impedance and relatively high output impedance (Sedra et al., 2004). One of the general uses of op-amp 741 circuit and the schematic diagram of the 741 op amp are shown in **Figure 1:**. a-b. The values R_1 and R_f define the real gain A, which is given by $A=1+R_f/R_1$ for the op-amp 741 (Terrell, 1996). Here, when R_f and R_1 are chosen 10 kΩ and 1 kΩ, respectively in this circuit, the real gain of the op-amp 741 is found to be 11. The real gain of system can be adjusted by changing resistance ratio.

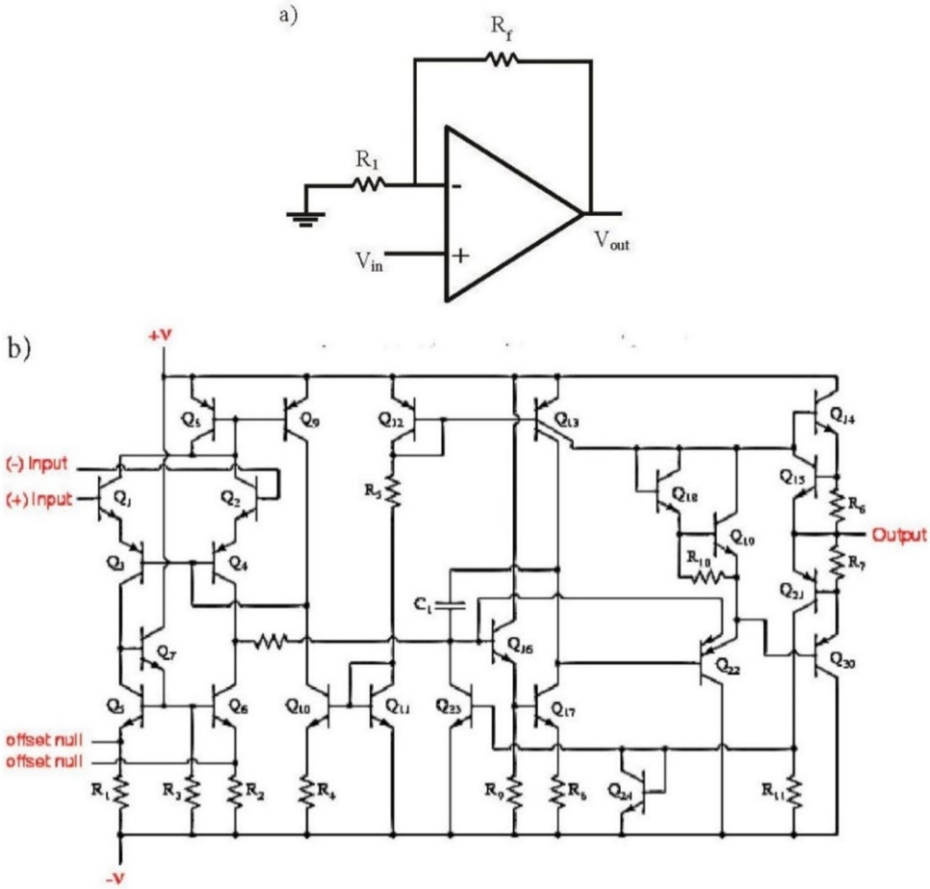

Figure 1:
The bias configuration and b) the schematic diagram of the 741 op amp

An important parameter for the operation of op-amps is the slew rate. The slew rate is defined as the maximum rate of change of the output voltage per unit of time and is expressed as volts per second (Terrell, 1996; M Fiore, 2018). Figure 2 shows the illustration of the slew rate for a square input signal, and the output signal presents with the red line in the figure. Here, for a given input amplitude, V_p and frequency, *f*, the slew rate is calculated by Eq. 1.

$$\frac{\Delta V}{\Delta t} = 2\pi f V_p \tag{1}$$

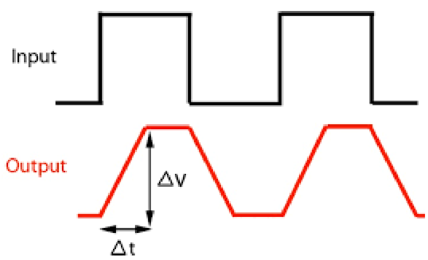

Figure 2:
The illustration of slew rate of op-amps

One of the mostly used component of electronic devices is the 555 single timer circuit (Cameron, 2021) in Figure 3. a. The 555 single timer has 23 transistors, 2 diodes, and 16 resistors, and the schematic diagram of this component is illustrated in Figure 3. b. The 555 single timer integrated circuit produces a square wave signal, and the output signal is presented in Figure 4. The time period can be adjusted by choosing different R_1, R_2 resistor and C capacitor values in the circuits (Sharma, 1978; Jung, 1977). The charge time (output high) and the discharge time (output low) for the 555 single timer can be calculated with $t_1=0.693(R_1+R_2)C$ and $t\_2=0.693(R_2)C$, respectively. Thus, the total period of this circuit is $T=t_1+t_2=0.693(R_1+2R_2)C$. The duty cycle of the circuit is defined as the ratio between the pulse duration and the period of a rectangular waveform. This ratio is used to set between output and input voltages, and the duty cycle (D) of the circuit can be found by Eq. 2. The output frequency (f) of oscillation of the circuit is given by Eq. 3.

$$D = \frac{R_2}{(R_1 + 2R_2)} \tag{2}$$

$$f = \frac{1}{T} = \frac{1.44}{(R_1 + 2R_2)C} \tag{3}$$

In the circuit, the duty cycle must be determined to be 50 %. Under this percentage, the additional components are needed to provide the successful output signal of the circuit. When the 50 % duty cycle is chosen, R_1 is 0 in Eq. 2 and, so t_1 and t_2 are equal. For example, when R_2=72 kΩ is used in the circuit, the capacitor C is 10 µF. The frequency of 1 kHz is calculated by Eq. 3.

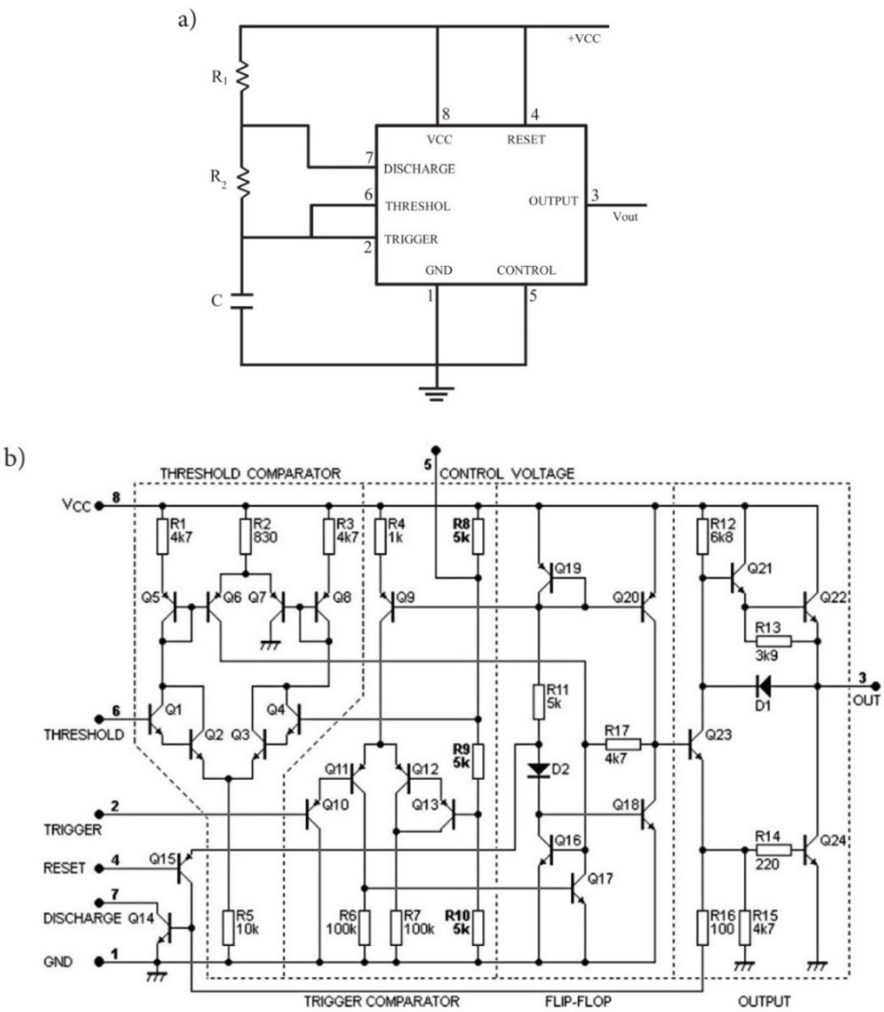

Figure 3:
a) General setup of the circuit with using 555 single timer b) the schematic diagram of the 555 single timer

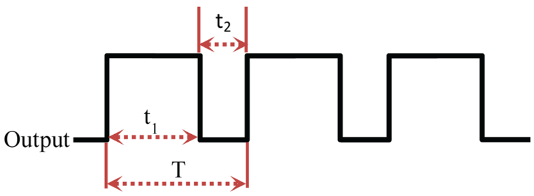

Figure 4:
The output waveform of 555 single timer circuit

In this study, we used the commercially available 8-pin 741 op-amp and 555 single timer chip. The test setup was designed, as seen in Figure 5. The ±9 V supply voltages were used in the integrated circuits and the 9 V, and the inputs and outputs of the integrated circuits were grounded to prevent signal fluctuating. We used new batteries (long lifetime) instead of a power supply to reduce the noise level. The components are configured with voltage trackers for both testing and irradiation. In this setup, the Co-60 source was used to expose gamma rays. The total radiation dose levels used to be 2 kGy and 4 kGy, and the dose rate was calculated as 0.37 Gy/s. The signal generator, oscilloscope, and computer for both 555 single timers and op-amp 741 circuits are located behind the concrete wall in a non-radiation environment. The components such as resistor, capacitor, and connector were tested with 4 kGy gamma radiation and they were not affected. Also, the temperature of the environment was checked with a thermocouple and the experiment was performed at room temperature.

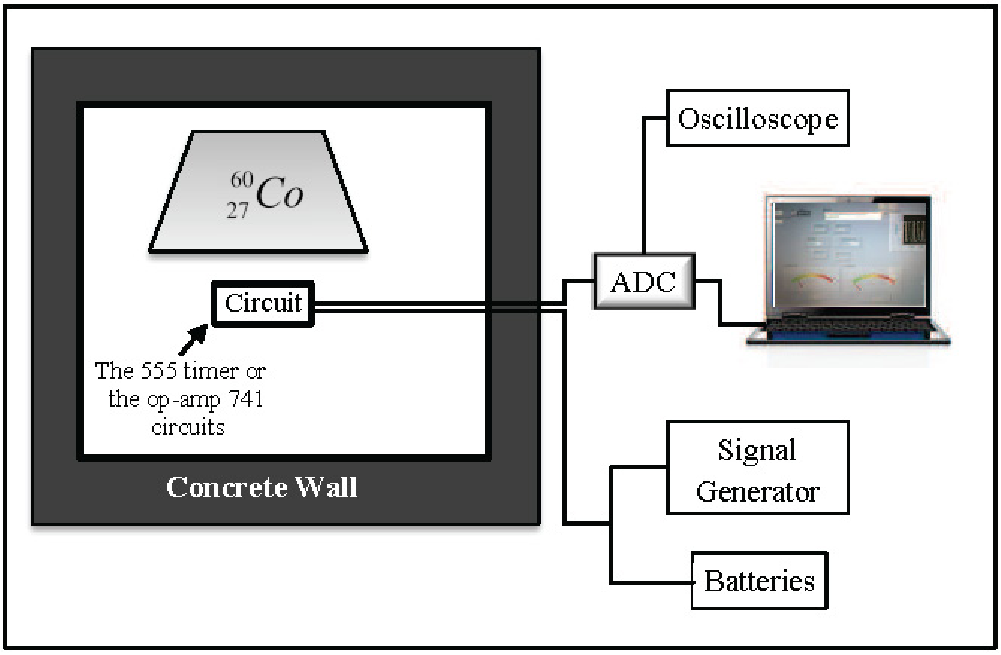

Figure 5:
The experimental diagram for the op-amp 741 and the single timer 555

Astable multi-vibrator circuit was designed by using 555 single timer ICs in Figure 1. a. and the integrated circuit with the 741 op-amp was set as seen in Figure 3. a. The acquisition data were controlled and collected using the virtual instrument software (LabVIEW) via a written program by ourselves. The frequency and the amplitude of the output signal of the circuit were recorded as a function of the radiation dose. The signal of the astable multi-vibrator was a square wave at frequencies 1 kHz, which was obtained from the signal generator. The output signals were monitored by an oscilloscope. The electrical parameters were measured depending on the frequency, the amplitude, and the slew rate. Here, the frequency is recorded by applying the Fourier transform.

3. RESULTS AND DISCUSSION

Figure 6. a and b show the change of frequency and amplitude in the 555 single timer chip as a function of the radiation dose. The data were recorded to observe the changes, continuously. As seen in Figure 6. a, the frequency of the astable multivibrator is stable until 270 Gy dose and oscillates at 202±0.4 Hz. The oscillation of the frequency began to increase above 270 Gy and suddenly dropped from 202 to 195 Hz at 744 Gy. When the radiation dose was increased from 744 to 930 Gy, a small drop occurred in the frequency and similar behaviors were observed due to the radiation dose. When the radiation dose was 3400 Gy, the frequency oscillated at around 194 Hz. On the other hand, the amplitude of the astable multivibrator tents to decrease linearly in the Figure 6.b. The amplitude decreases from around 5.02 to 4.81 V as the radiation dose increases. A jump was observed at 744 Gy and the amplitude quickly jumped

from a maximum to a minimum at doses such as 930, 2000 and 2500 Gy, which a small drop was occurred in the frequency. The results show that the 555 single timer is resistant until 270 Gy and loses its skill at 744 Gy dose. A decrease in the frequency indicates that the period of the 555 single timer increases and the period depends on the resistances and a capacitor as seen in Eq. 3. Here, *C* is *q/V* and the applied voltage is constant and, hence, the *q* must change with the radiation. A decrease from 202 to 195 Hz in the frequency caused around 4 % increase in the *q* for the integrated circuit with the 555 single timer.

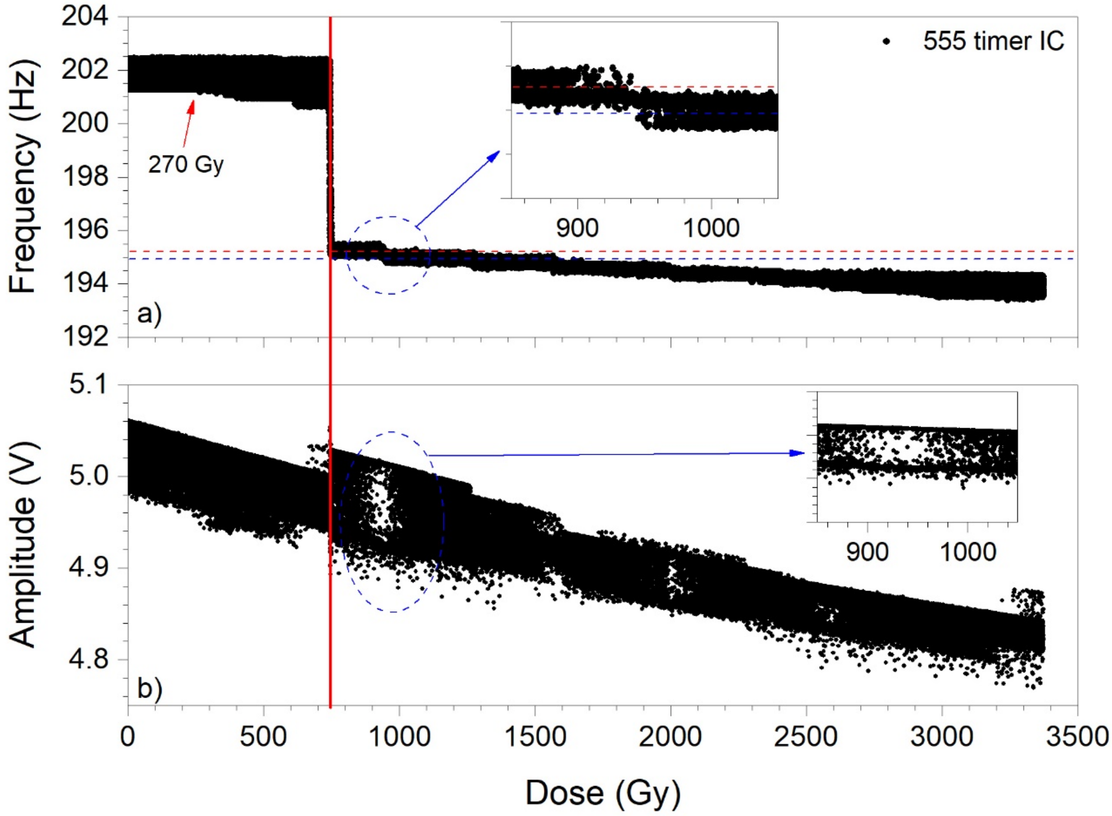

Figure 6:
The variation of a) the frequency and b) the amplitude with the dose

It is well known that the internal structure of the 555 single timer includes 2 diodes and 23 transistors, and these are semiconducting *pn* and *npn* (*pnp*) junctions, respectively. When gamma radiation of sufficient energy interacts with semiconducting junctions, it causes ionizations and/or atomic displacements leading to crystal structural defects in the form of vacancies, defect clusters, the change in the band gap and dislocations (Lai et al., 1995; McPherson et al., 1997; Van Lint, 1987). These defects can lead to the formation of energy levels within the band gap which can act as trapping and recombination centers for carriers and are due to the radiation dose and the structure of the material. As an example, the optical band gap shows an increase for $CuInSe_2$ (Dewan et al., 2008), while it is found to decrease for SnO (Abhirami et al., 2013). The previous studies show that the diodes, which is two-terminal devices, are very sensitive to small levels of radiation and it produces a high leakage current (Arshak and Korostynska, 2004; Arshak and Korostynska, 2004). Li et al., have shown that the ionized radiation on *npn* transistors causes an increase at base current (Li et al., 2010). Consequently, the diodes and transistors of the 555 single timer directly affected by the radiation and the leakage current increases in the integrated circuits, and hence, the amount of *q* begins to rise. Our results indicate that it does not hardness to gamma radiation. The results show that the threshold of gamma ray radiation is 744 Gy for 555 single timer chips and the frequency affects in this radiation dose.

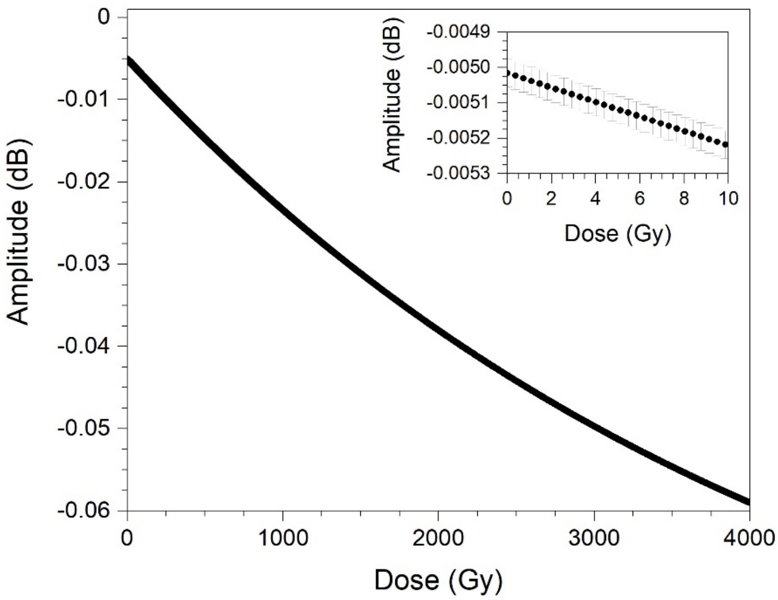

Figure 7:
Output signals of the amplitude of 741 op-amp as a function of radiation dose

The amplitude change of the 741 op-amp circuit versus the gamma radiation dose is shown in Figure 7. We applied an exponential fit function to experimental data with Eq. 4. Here, A and R_0 are initial value and rate parameter, respectively. The obtained initial values are 0.02631 for A. The R_0 is -2.29x10^{-4}. The amplitude signal of the 741 op-amp decreases to -0.054 dB value due to increasingly the gamma dose. The inset figure in Figure 7 is zoom of the main figure and is shows the error bars of the data.

$$y = y_0 + Ae^{R_0 x} \tag{4}$$

In

Figure **8**. a and b, the input and output frequencies of the 741 op-amp are presented. The frequency on 741 op-amp applied square signal and the input signal oscillated between 1043 and 1000 Hz before the radiation. The dominant frequency was found about 1043 Hz as seen in the figure. In

Figure **8**. b, the output frequency changed in the range of 1012-1043 Hz in lower radiation dose and when the radiation dose increased up to 200 Gy, the lower limit of frequency also increased. The 741 op-amp includes a capacitor, 12 resistors and 20 transistors. The transistors are semiconducting *npn* or *pnp* junctions and hence, the amplitude and frequency of the integrated circuit with the 741 op-amp are affected by the radiation. But, the hardness of the 741 op-amp is more than that of the 555 single timer. Here, the difference of the 741 op-amp is that does not include any diodes when it compares with the 555 single timer and the results show that the radiation sensitivity of the semiconducting *pn* junctions is much more than the *npn* junctions.

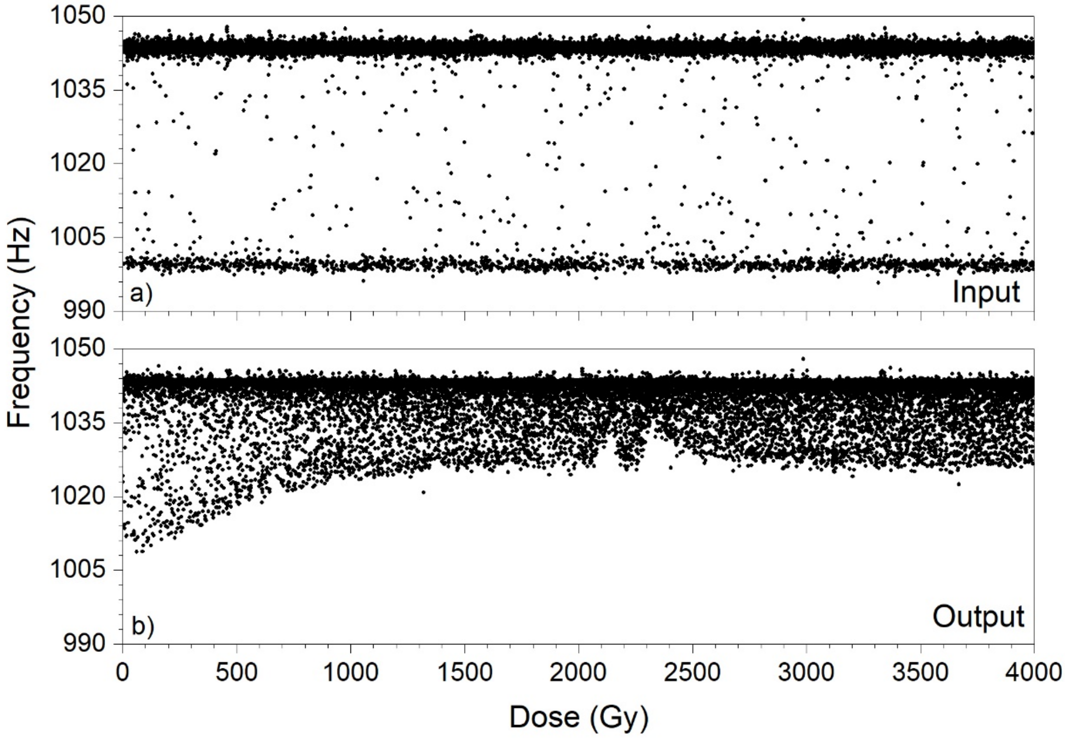

Figure 8:
a) Input and b) output signals of the frequencies of 741 op-amp as a function of radiation dose

The general-purpose op amps contain a compensation capacitor that is used to control the open loop frequency response. The signal developed across this compensation capacitor is amplified to create the output signal and this capacitor serves as the load inside of the op-amp. This compensation capacitor can be charged a certain rate, which is determined by a charge equation (M Fiore, 2018):

$$i = C\frac{dv}{dt} \qquad (5)$$

$$slewrate = \frac{dv}{dt} = \frac{i}{C} \qquad (6)$$

The *dv/dt* parameter is called slew rate (Eq. 6), which is very important in that it helps determine whether or not a circuit can accurately amplify high-frequency or pulse-type waveforms. In order to create a fast op amp, either the charging current *i* must be large, or the compensation capacitor *C* must be very small. Therefore, the slew-rate of the 741 op-amp is an essential parameter for applications. We monitored the slew rate on the oscilloscope as seen in **Figure 9 :**. a and b. As seen in

Figure **9**. a, the slew-rate before the radiation was calculated as 4 V/µs with using Eq. 1. After the irradiation, the input slew-rate was found the initial value as seen in

Figure **9**. b, however, retardation was observed in the output signal. The slew rate was found about 0.65 V/µs. The result show that the rate of the 741 op-amp slows down due to radiation.

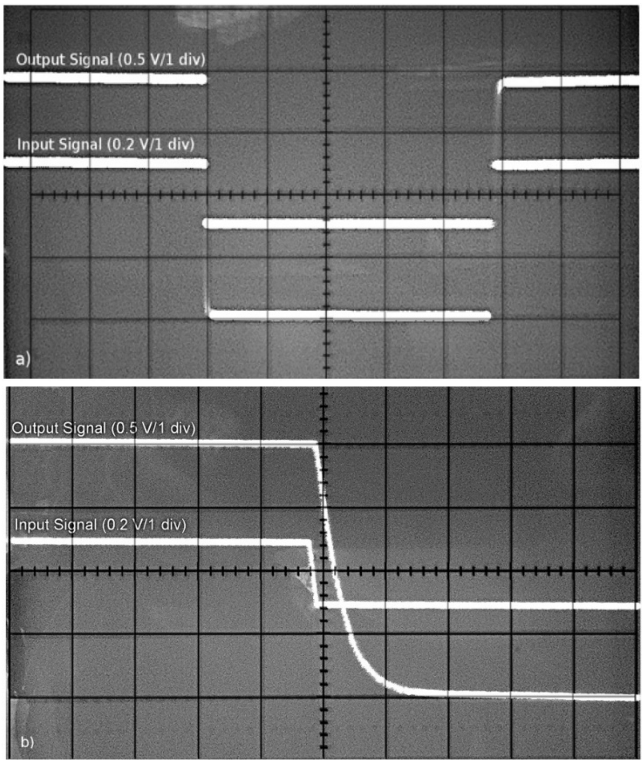

Figure 9 :
The slew-rate of 741 op-amp (a) before irradiation (b) after irradiation

4. CONCLUSIONS

In this study, the commercial 555 single timer and the 741 op-amp circuits were investigated under the gamma ray radiation. In the 555 single timer circuit, we observed the abnormal behaviour in the frequency which decreases from 202 to 195 Hz (the loss is about 4 %) at 744 Gy gamma ray radiations. In this state, an increase was occurred in the flowing charges (4 %). At the same time, the amplitude of the integrated circuit with the 555 single timer tends to decrease linearly with the increasing radiation dose. This result shows that the 555 single timer has to shielded from the high level radiation, nevertheless, it can tolerate the lower level radiation dose (270 Gy). In 741 op-amp circuit, the amplitude signal of the 741 op-amp shows a maximum value of -0.054 dB at 4 kGy gamma dose. In the results of this, the slew rate of the 741 op-amp decreases from 4 to 0.65 V/µs. Consequently, both the 555 single timer and the 741 op-amp include a number of resistors and *npn* or *pnp* type transistors, and also, the 555 single timer has two *pn* diodes in its structure. These diodes cause that the 555 single timer is easily affected by the gamma radiation when it compares with the 741 op-amp. The 741 op-amps and 555 timers have generally minimum and maximum voltage, current and/or temperature values in their datasheets. Hence, the stable values are used to obtain "good" results. The changes or jumps of frequency and amplitude causes the variation of charge, which flows on it. This change occurs the oscillations in both voltage and current. The oscillations directly affect the charge movements from the valence to conduction bands in the semiconductors, causing the decrease of efficiency of the transistors. For example, when the time of exposure the radiation increases in the 555 single timer, it causes an increase in the temperature of the semiconducting material. In the semiconductor, mobility and carrier concentration are both temperature-dependent. When the temperature is increased in a semiconductor, both the electrons and the atoms gain more energy. When the electrons gain more energy, the atoms vibrate more, increasing the scattering of electrons. Their energy gap between the conduction band and valence band decreases with an increase in temperature. The valence electrons in the semiconductor material gain energy to break the covalent bond and jump to the conduction band at high temperatures. Consequently, the temperature increases unexpectedly. Therefore, the semiconducting material begin to take the damage. These two important components for the applications are affected by the gamma radiation and therefore, these are shielded by the material that has high radiation resistance.

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CONFLICT OF INTEREST

Author(s) approve that to the best of their knowledge, there is not any conflict of interest or common interest with an institution/organization or a person that may affect the review process of the paper.

AUTHOR CONTRIBUTION

Dr. Esra Kendir Tekgül: determining the concept and design process of the research and research management, data collection and analysis, data analysis and interpretation of results, Preparation of the manuscript, Critical analysis of the intellectual content, final approval and full responsibility of the study. Dr. Şerafettin Yaltkaya: determining the concept and design process of the research and research management, data collection and analysis, data analysis and interpretation of results, Preparation of the manuscript, Critical analysis of the intellectual content, final approval and full responsibility of the study.

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