VOL. 18, NO. 11, JUNE 2023 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

RESEARCH ON THE EXPOSURE OF RADIO-ELECTRONIC EQUIPMENT TO ULTRASHORT ELECTROMAGNETIC PULSES AND MICROWAVE RADIATION

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ABSTRACT

The paper considers two methods of exposure of radio-electronic equipment to ultrashort electromagnetic pulses. The methods of exposure to ultrashort electromagnetic pulses differ in the delivery of radiation energy to the IC. According to the first method, the circuit is placed in an electromagnetic field with the set amplitude frequency response. The second method implies that microwave pulses are injected directly onto the circuit pins. Thus, the main research is aimed at an experimental assessment of the stability of radio equipment and its components to ultrashort electromagnetic pulses and microwave radiation. It describes various dependences of the malfunction index for some integrated circuits (ICs) on the duration of ultrashort electromagnetic pulses and microwave radiation energy. ATmega32A and STM32F microcontroller ICs are used in the research. The paper presents findings on the stability of the IC to the exposure to of ultrashort electromagnetic pulses and microwave radiation about the manufacturing technology, i.e. the housing manufacturing techniques. Following the research, the main feature characterizing the effectiveness of exposure of microcontrollers is the amplitude of the impacting pulses.

Keywords: database radio-electronic equipment, ultrashort electromagnetic pulse, microwave radiation, integrated circuit, microcontroller.

Manuscript Received 28 February 2023; Revised 30 July 2023; Published 13 August 2023

INTRODUCTION

Modern electronic advance, as well as the growing dependence of the population on information technology, has caused the newest type of danger, namely electromagnetic terrorism. It includes destructive electromagnetic exposure of radio-electronic systems to destroy them or disrupt their operation. In this regard, studying exposure to ultrashort pulses and microwave radiation is relevant in the scientific world. Generally, researchers focus on exposure to high temperature and humidity combined with the supply voltage or analyze the radiation resistance of ICs. Very few methods have been used to assess the resistance to electromagnetic effects in an electromagnetic field with a set amplitude frequency response and directly on the radio-electronic equipment.

Methods of protection against intentional exposure of radio-electronic equipment to ultrashort electromagnetic pulses or microwave radiation are currently considered under-investigated. The most interesting way to assess the vulnerability of electronic systems is an experimental method that shows dangerous levels of information infrastructure exposure with certain accuracy.

LITERATURE DATA ANALYSIS AND PROBLEM STATEMENT

In article [1], the authors examine the influence of the complex impact of climatic factors (temperature, humidity) and electrical mode (supply voltage) on the corrosion resistance of metallization of integrated circuits. They proposed a method for assessing the corrosion resistance of aluminium metallization in depressurized CMOS of integrated circuits.

In [2], the authors analyze tools for the calculation of the electrical performance of several devices built on integrated circuits and operating under various external conditions, such as temperature, electric field, or radiation.

Paper [3] develops a method of accounting for various uncontrolled parameters arising during microcircuit manufacturing. Adjustment is performed by changing the influencing impacts from the control system in such a way as to compensate for the exposure to non-random external influences by changing the parameters of specific technological operations during the release of new batches.

Article [4] is devoted to the influence of the offset connecting line voltage on the measurement of the contrast of the internal current of the integrated circuit using magnetic force microscopy. The article proves the influence of the offset connecting line voltage on the measurements of the internal current of integrated circuits.

In article [5], the influence of heat sink structures on the thermal behaviour of photonic integrated circuits is studied, paying special attention to maximizing the efficiency of thermoelectric modules. For this purpose, closed analytical and numerical models have been developed for a representative laser matrix of an integrated photonics circuit that captures the conductive heat exchange inside the distributor in combination with the defining representation of the thermoelectric module.

The article [6] presents a method for determining the effect of thermomechanical stresses on the reliability of metal lines made of various aluminium alloys. The samples were thermocycled from -65 °C to +160 °C. Two different electrical test methods were then applied and the data were compared to determine a possible change in electrical load capacity due to temperature treatment.

These works [1-6] use natural influences, such as temperature, humidity, supply voltage, electric field, and voltage of displaced connecting lines to study the impact on the IC. The stability of radio equipment and its components to ultrashort electromagnetic pulses and microwave radiation was not considered. When processing digital data, the duration of operating and acting pulses are comparable. This is considered a characteristic feature of this type of radiation. For this reason, when the ultrashort electromagnetic pulses influence electronic equipment, signals similar to operating ones are induced in their elements and units. This disrupts the operation of the radio-electronic equipment components. The remote destruction of the IC of radio-electronic equipment, as well as data transmission and processing systems created on their basis, is one of the likely application areas of such emitters. To date, the microcircuit is the main element in the radio-electronic system, operating at high frequencies and very low voltage. Therefore, it becomes most susceptible to ultrashort electromagnetic pulses.

In the article [7], the authors compared the radiation resistance of promising bipolar and heterobipolar transistors. The features of electronic transport in the active regions of transistors are analyzed and the effect of a burst of velocity and diffusion of quasi-ballistic electrons on increasing the radiation resistance of transistors is estimated.

In [8], an experiment was conducted on irradiation with heavy ions in digital storage cells with different design approaches in the technologies of bulk silicon CMOS 130 nm and silicon on an insulator. The efficiency of linear energy transfer with an inclined ion beam at a 130 nm process unit is obtained.

In the article [9], the authors analyzed the resistance of signal converters with an operating frequency of 57-64 GHz produced on $AlGaN/GaN/Al_2O_3$ heterostructures to the action of special conditions such as neutron, gamma radiation, and the establishment of their long-term stability at colossal temperature.

In [10], functional and logical modeling of large-sized digital integrated circuit degradation under the influence of radiation is considered. Methods of modeling the radiation reliability of digital large-size integrated circuits based on fuzzy Brauer digital automata and topological-probabilistic performance evaluation models are described.

In [11], the effect of X-ray radiation on the low-frequency noise of integrated circuits was studied. The sensitivity of various parameters of integrated circuits developed by different technologies to X-ray radiation and the possibility of predicting the level of low-frequency noise is considered.

In [12], the influence of a flux quantum trapped in a superconducting grounding hole called a ditch, on the operation of a superconducting circuit is analyzed. A calculation model has been developed to estimate the magnetic flux penetrating the signal line of a superconducting integrated circuit due to the captured flux quantum in a ditch located next to the signal line using a conventional inductance extraction tool.

Works [7-12] studied exposure to various radiations. However, the effects of ultrashort electromagnetic pulse and microwave radiation have not been studied. To date, the means of electromagnetic influence on radio-electronic equipment are rapidly being formed, especially the means of influence created on the latest physical principles. The newest powerful generators of microwave radiation have been designed, emitting single and periodic ultrashort electromagnetic pulses, which have ultra-wide bandwidth and a huge amplitude that are absent from conventional sources of intentional interference. Their spectral density is distributed in the range from 100 MHz to 1 GHz.

In [13], the surface scanning method was used to determine the characteristics of printed circuit boards and integrated circuits in terms of electromagnetic radiation and noise immunity. This is a method for detecting areas of critical radiation or susceptibility that may affect the operation of nearby devices or the device under test itself.

Article [14] considers the probability of IC failure under the influence of pulsed radio emission. A theoretical development of the damage accumulation model is proposed to explain the observed effects of damage to integrated circuits by multi-pulse radio emission.

Article [15] analyzes the influence of the power supply on the emitted electromagnetic radiation of integrated circuits. A test chip is presented, as well as a measurement method for investigating these measures by future design recommendations.

Papers [13-15] do not consider experimental methods for resistance to electromagnetic influence, differing by the method of microwave radiation and ultrashort electromagnetic pulses, on radio-electronic equipment. In the first method, the circuit was placed n an electromagnetic field with a set amplitude frequency response. The second method implies that microwave pulses are injected directly onto the circuit pins.

Work [16] investigates the influence of various factors, including electromagnetic radiation, on reed switches in electronic devices based on microprocessors.

In [17], the authors examined the effect of the flow of high-speed microparticles on the parameters of integrated circuits placed behind a thick-walled obstacle. Experimental data shows that when a stream of high-speed microparticles (in terms of parameters close to cosmic particle flows) collides with a thick-walled metal obstacle, integrated circuits located behind this obstacle fail.

In [18], the effect of metallization thickness on the stability of integrated circuits under the influence of electromagnetic fields is considered. The method of numerical calculation of the resistance of integrated circuits depending on the thickness of metallization under the influence of pulsed electromagnetic fields is given.

The article [19] analyzes the influence of conductor systems on crosstalk in integrated circuits. The distances between the terminals are determined, as well as the use of multilayer connecting systems that cause parasitic electromagnetic connections.

In [20], the authors examined the influence of the shape of the microchannel and magnetic material on the magnetocooling of integrated circuits. The influence of the thickness of the magnetic material on performance is also investigated.

Article [21] considers the effect of chemical treatment on tungsten films in integrated circuits. The effect of four different chemical solutions on the composition, morphology, and etching rate of tungsten thin films deposited chemically from the vapor phase was investigated.

In [16-21], the authors analyze the difference in IC stability against exposure to ultrashort electromagnetic pulses and microwave radiation about the type and technology of IC manufacturing.

Thus, the analysis of the literature shows the possibility of using the exposure of an IC to intentional radiation. At the same time, there is a gap in the study of methods for assessing the impact of ultrashort electromagnetic pulses on ICs. This sets the task of investigating two (direct and indirect) ways to assess such an exposure. In this regard, the authors formulated the idea of research based on an experimental assessment of the stability of radio equipment and its components to ultrashort electromagnetic pulses and microwave radiation. The research should be carried out for radio-electronic devices based on the most common microcircuits.

PURPOSE AND OBJECTIVES OF THE RESEARCH

The purpose of the paper is to study the exposure of radio-electronic equipment to microwave radiation and ultrashort electromagnetic pulses in two ways (direct and indirect). The study of radio-electronic equipment components for resistance to microwave radiation shall allow the developer to compare different components and, when designing radio-electronic equipment, give preference to more resistant ones or decide on the use of additional shielding of less resistant components and assemblies.

Objectives:

- analyze the difference in IC stability against exposure to ultrashort electromagnetic pulses and microwave radiation about the type and technology of IC manufacturing;
- study the dependence of the IC stability on the characteristics of the impacting pulses.

MATERIALS AND METHODS OF RESEARCH

Article [22] considers two different ways of performing an experiment for resistance to electromagnetic influence, differing in the scheme of radiation energy delivery to the IC. According to the first method, the circuit is placed in an electromagnetic field with the set amplitude frequency response. The second method implies the injection of microwave pulses, whose characteristics correspond to those of electromagnetic incident radiation, onto the microcircuit terminals.

The two methods have their advantages and disadvantages. The first method guarantees the greatest compliance of the influence characteristics with the conditions of documents standardizing the influence directly in the parameters of the electromagnetic field. However, this method cannot be performed in every case. Therefore, it is not able to guarantee the study of all components and units of the radio-electronic equipment. In addition, the results of the first method will significantly depend on the characteristics of the circuits (loop, housing, or printed circuit board). This in turn leads to a decrease in the reliability of the data obtained.

The main advantage of the second method is considered to be the selectivity of influence, which increases the authenticity of the information received (since the tested component or unit of the radio-electronic equipment is directly affected). In addition, the second method requires a microwave unit that has less power compared to the equipment used to implement the first method. Apart from that, the second method allows adapting the results of empirical studies to use in computational and empirical methods with a high degree of reliability. In some situations, the second method guarantees significantly worse exposure adequacy than the first method. This is due to the lack of methodological instruments linking the characteristics of the electromagnetic field in free space specified in regulatory documents with the parameters of the microwave pulse in the supply feeder and the impossibility of synchronous influence on all components and units of the radio-electronic equipment.

According to the work considered in the paper [22], the study of the stability of the radio-electronic equipment components was implemented by the first method. Here, when analyzing the stability of the IC, going beyond the limits of the standard technical conditions of the main characteristics of the microcircuits was used as a stability criterion [23]. The most popular types of circuits were selected for the study as follows [24]: ATmega32A-PU, ATmega32A-AU, ATmega8-PU, STM32F103C8T6. It should be noted that the ATmega32A microcontroller is used in two different types of DIP and TQFP housings. This is necessary to study the exposure of the chip to ultrashort electromagnetic pulses, depending on the housing type. Microcontrollers are programmed to generate a binary sequence.

The following characteristics of microcircuits are selected; when they go beyond the levels set in technical specifications, it is considered a failure criterion:

- output voltage at the pins of the circuits;
- time interval from input to output pulses during the transition of the voltage at the output of the circuit from the logical zero voltage to the logical one voltage (or vice versa);

- the number of erroneous bits of transmitted information that the microcontroller transmits curcuitwise from one output to another while comparing the transmitted and received bits.

The level of failure-free operation of the circuits at the established time, as well as spectral characteristics of the exposure, shall signify the stability of microcontrollers.

RESULTS

Figure-1 shows the research method where a circuit is placed in an electromagnetic field.

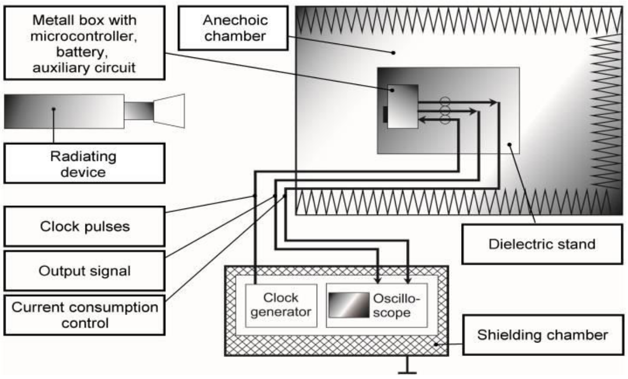

Figure-1. Direct method for the research of components and units of radio-electronic equipment.

To minimize the effects of microwave radiation on the auxiliary equipment operation, the following has been performed:

- the pulse generator used, the oscilloscope, as well as electronic computing equipment, were located at a great distance from the spot of microwave radiation in a shielded space, which was achieved due to the use of a repeater switched on between the oscilloscope under study and the IC;
- batteries were used to power the studied circuits;
- the battery, the switching circuit, and the repeater shown in Figure-2 were located in an iron box with a large shielding coefficient.

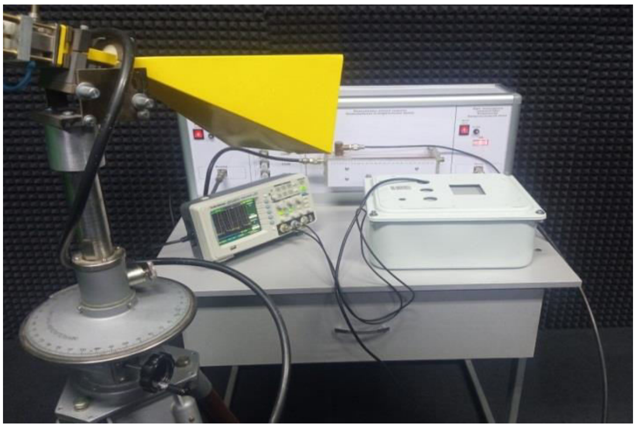

Figure-2. Experimental setup in an anechoic chamber.

The circuits installed on printed circuit boards, in which in turn all the passive components necessary for their operation were located, were irradiated and switched on in standard modes. The dimensions of the irradiated printed circuit boards were 50x70 millimeters, as shown in Figure-3.

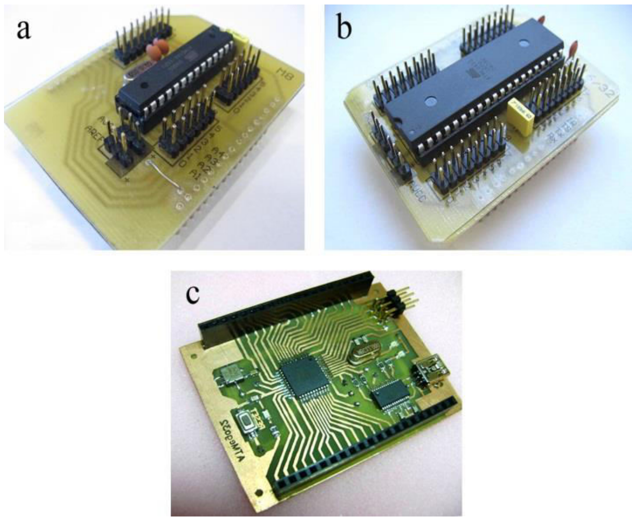

Figure-3. The exterior of irradiated printed circuit boards with ATmega8 and ATmega32A chips is installed in DIP and TQFP cases.

To clarify the quality of the unit's functioning, a series of preliminary studies were conducted studying the effect on ATmega32A microcircuits by microwave pulses with a carrier frequency of 2.5 GHz and the highest energy flux density of 40 W/cm achieved during testing, as well as ultrashort electromagnetic pulses with a duration of 300 ps and an electric field strength of 40 kV/m.

Provided that the test facility is irradiated with electromagnetic fields of similar power, the repeater and the switching circuit guarantee the correct operation of the circuit under study [25], and the measuring device makes it possible to record signals from the output of the microcontroller almost without distortion. The reaction of the ATmega32A circuit to the exposure is shown in Figure-4.

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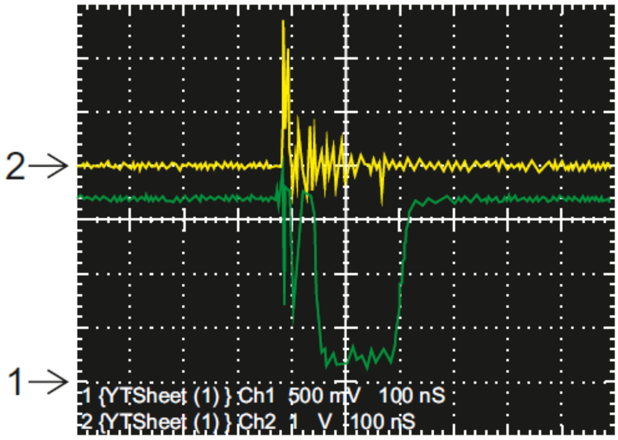


Figure-4. Waveforms of ATmeda32A microcontroller's exposure to ultrashort electromagnetic pulses.

The ГИН-60950-2 ultrashort electromagnetic pulse emitter was used as an electromagnetic emission generator.

When implementing the second method of testing, the exposure was performed directly on the pins of the microcircuits. An antenna decoupling was used to transfer the energy of the ultrashort electromagnetic pulses to the input of the object. The same units as in the first method were used as emitters. The injection scheme is shown in Figure-5.

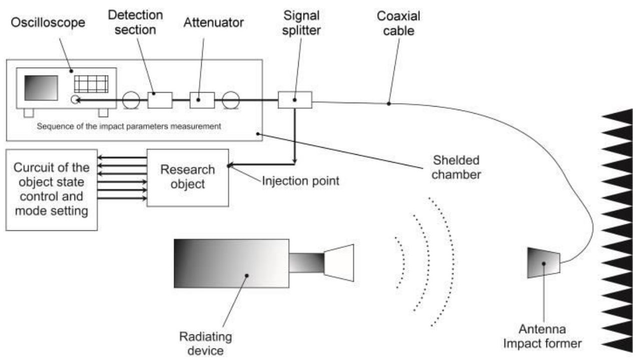


Figure-5. Scheme of microwave pulse injection using antenna plastic decoupling.

The SAS-510-2 broadband log-periodic radio antenna was selected during testing for resistance to narrowband influence. In this case, the time form of the microwave pulse was transmitted to the input of the test object almost without distortion.

The АИР-18М horn converter was used as an antenna when testing for resistance to ultra-wideband influence. Tests have demonstrated that the electromagnetic pulse falling into the antenna has an ultra-wide range; it is significantly distorted in a rather narrow-band receiving antenna-feeder circuit.

DISCUSSION OF THE RESULTS

The performed studies revealed a rather significant susceptibility of microcircuits to the influence of ultrashort electromagnetic pulses and microwave pulses of microsecond duration. The test results (Table-1) significantly depended on the properties of the acting signals and the type of circuit.

Table-1. Pulse signal properties leading to malfunction of microcircuits.

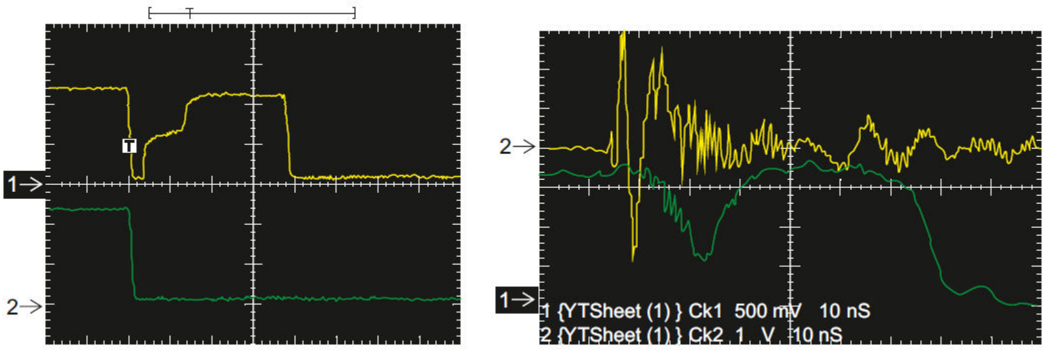
Microwave and ultrashort pulse parameters	Microcontroller		
	Atmega32A (1 MHz, DIP, U_{pit} = 5V) , V	Atmega32A (1 MHz, TQFP, U_{pit} = 5V) , V	STM32 (24 MHz, LQFP, U_{pit} = 3.3V) , V
Ultrashort pulse 1 GHz; 50 ns	40-150	20-150	20-150
Microwave 0.5 GHz, 1 µs	8-12	7-16	6-15
Microwave 0.8 GHz, 1 µs	10-29	7-18	7-19
Microwave 1 GHz, 1 µs	14-49	9-22	8-27
Microwave 3 GHz; 1 µs	15-65	12-57	14-64

In all experiments, the result of the exposure was a change in the voltage at the output of the circuit. Depending on the properties of the injected signals, as well as the type of microcontroller, it could cause the following consequences.

a) A change in the logical state at the output of the microcontroller at the time that is the same or exceeds the duration of the acting pulse. Exceeding the duration of the IC failure over the duration of the interference is more typical for the influence of the ultrashort electromagnetic pulses. For some microcontrollers, in turn, an increase in the time of loss of operability was recorded with an increase in the level of the acting voltage (power). The analyzed results are typical for the option when the duration of the interference is much less than the period of the clock pulses of the microcontroller. Examples of the ATmega32A output signal under the action of a microwave pulse with a duration of 1 µs and an ultrashort pulse with a duration of 50 ns are shown in Figure-6. In the second case, the switching of the microcircuit

ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

happened after the end of the exposure to ultrashort electromagnetic pulses (Figure-6b).



a) b)

Figure-6. The signal on the ATmega32A-PU pin (channel 1) under the exposure to an interference microwave pulse with a duration of 1 µs (a) and 0.5 ns (b).

b). Data distortion at the output of the microcontroller. A sample of data distortion by the ATmega32A microcontroller is shown in Figure-7.

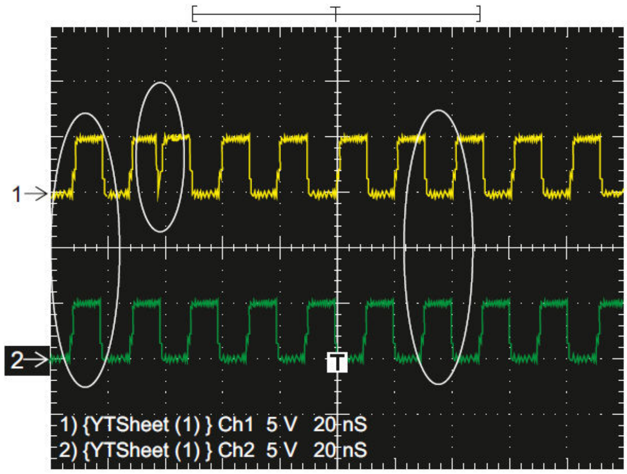


Figure-7. Signal types received from the ATmega32A control output on channel 1 and the control sequence on channel 2.

It is obvious that before the exposure, the output voltage changed simultaneously with the control one. However, after the exposure, the situation changed significantly, since the microcontroller did not register the affecting ultrashort electromagnetic pulses.

c) Suppression of the output information signal of the IC for the duration of the pulse-interference influence and more. This effect is common in situations when the duration of the acting leads exceeds the duration of the clock pulses. It is shown in Figure-8.

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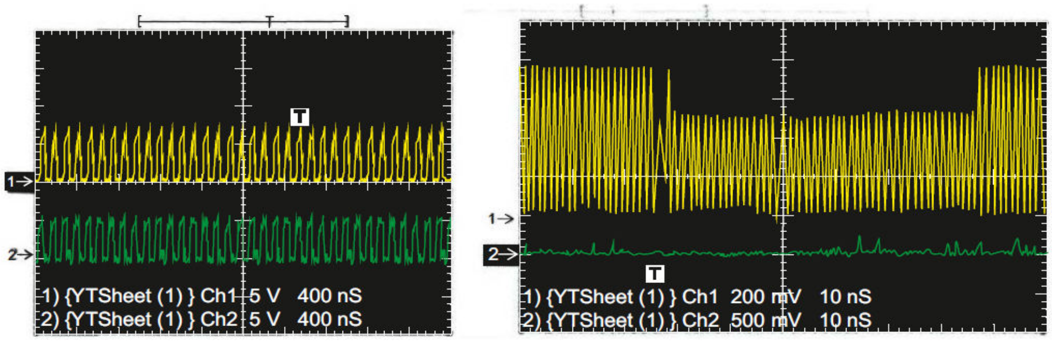
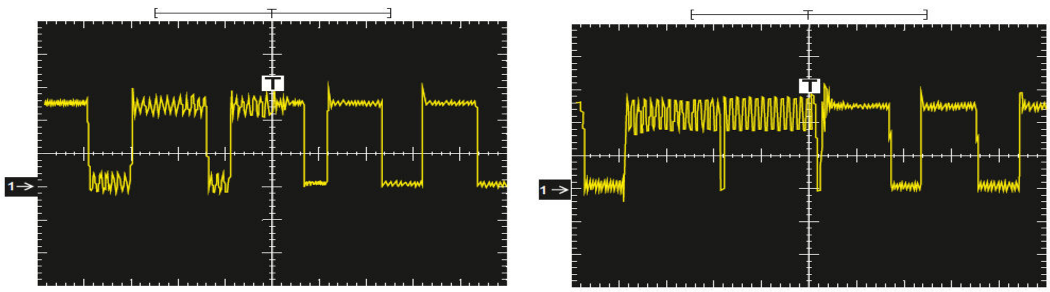


a) b)

Figure-8. The type of signal from the ATmega32A output on channel 1 and the control sequence on channel 2 under the exposure to a microwave pulse with a duration of 400 ns (a) and 2 microseconds (b).

d) Distortion of the time properties of the pulses at the output of the microcontroller. This result was observed when long radio pulses with a carrier frequency of 0.5 GHz and 0.3 GHz were applied to the circuit. The waveforms of the ATmega32A output voltage, when interference affects its logic input together with a frequency of 0.5 GHz, a duration of 40 microseconds, and a power of 1 W, are shown in Figure-9a. It is noticeable that a significant increase in the time interval occurs as a result of the effect; during this time, the microcontroller output remains in the state of a logical one. Figure-9b shows that the microcontroller transits to a time exceeding the duration of the acting pulse with a subsequent increase in the interference power to 1.5 W.



a) b)

Figure-9. ATmega32A output voltage when the logic input is affected by an interference pulse with a power of 1 W (a) and 1.5 W (b).

e) The failure and reset of the microcontroller were recorded at fairly significant levels and/or times of exposure. It is particularly typical of exposure of circuits to microwave pulses with a carrier frequency of 0.3-1 GHz.

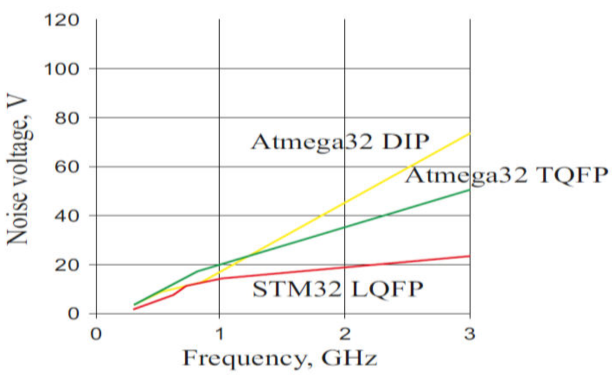


Figure-10. Graph of the microcontroller malfunction traces due to the carrier frequency of the acting microwave pulses 1 μs long.

Experiments on the exposure of microcircuits to microwave pulses one microsecond long allowed assessing the dependence of the level of microcontroller malfunction on the carrier frequency of interference pulses, which is shown in Figure-10.

Thus, the authors researched the exposure of radio-electronic equipment to ultrashort electromagnetic pulses and microwave radiation. The results of the research can be used for considering electromagnetic compatibility when designing radio-electronic equipment based on the studied microcircuits [26, 27]. In the future, it is planned to study the methods of protection against exposure to ultrashort electromagnetic pulses.

CONCLUSIONS

a. The resistance of microcontrollers to exposure to ultrashort electromagnetic pulses and microwave radiation is not closely related to the manufacturing technology of the housing.

b. Starting from the duration of 200 ns, the reset level of the microcontroller is almost not dependent on the duration of the acting pulse. The energy of the impacting pulse is not as effective as its amplitude. Therefore, the main parameter characterizing the effectiveness of influencing microcontrollers is considered to be the amplitude of the impacting pulses.

In frequencies up to 1 GHz, the influence of radio pulses on the IC is considered the most effective, in contrast to the influence of the ultrashort pulses, considering the pulse energy. The failures occur due to a change in the logical state of the circuits and are usually random and characterized by a wide variety of effects observed at the object level.

This research was funded by the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP13268732).

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