Analysis of Signal Integrity in a Microstrip Transmission Line on a Substrate of the Nanoconducting Dielectric

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***Abstract*—The paper presents the analysis of the signal integrity in microstrip transmission line with nanoconducting dielectric. It shows the results of calculating the passage of a sequence of pulses of trapezoidal shape to account for losses in copper. It is due to its finite conductivity and skin effect, which significantly affects the high frequency harmonics, and also to the loss in nanoconducting dielectric with a high end-to-end conductivity. It is shown that all these losses are small and the use of nanoconducting dielectrics for eliminating electrostatic discharge is justified.**

***Index Terms*—Nanoconducting dielectric, electrostatic discharges, signal integrity, microstrip transmission line, skin effect, dielectric loss.**

I. Introduction

THE most important problem during the prolonged operation of a spacecraft (SC) is the phenomenon of electrification and ensuing electrostatic discharges (ESD). This is related to the process of the SC surface charge accumulation that appears due to fluxes of ions and electrons of the cosmic plasma, and which leads to the formation of the potential difference of the device relative to the surrounding plasma. These processes occur most intensively during substorms in the Earth's magnetosphere.

The resulting potentials on the SC surface reach tens of kilovolts. SC charging occurs unevenly between the construction elements and the SC frame. A significant potential difference can initiate an ESD which undoubtedly leads to the occurrence of the electromagnetic interference in a wide range of frequencies for on-board electronic equipment. It causes failures of various on-board systems and can cause an irreversible damage to electronic components.

The present-day spacecraft are quite tolerable against an external electrification but later the most popular subject of research became the phenomenon of an internal electrification [1-2]. In the process of internal electrification, an electric charge accumulates in the dielectrics of electronic circuits due to penetration of corpuscular outside radiation, primarily electrons with energies of several MeV. This leads to the risk of an ESD initiation near the SC electronic circuits and circuit boards.

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II. Nanoconducting dielectrics

One of the fundamental directions in the study and prevention of SC electrification is the creation of new materials for the components of the on-board equipment, particularly materials for electronic printed circuit boards. In [3-6] it has been proposed a principally new concept of modern protection from the damaging factors of electrification - the concept of "nanoconducting dielectrics", which is expected to replace the current concept of the "Faraday's cage", which is subject to internal electrification. The basis of the proposed concept is a requirement that precludes the use of dielectric materials having an electric conductivity below the value of 10^{-10} $Ohm^{-1}m^{-1}$ while creating a new SC. Consequently, removal of charges from the volume of a dielectric occurs without starting an ESD and, therefore, properly protecting of the SC. Thus, a printed circuit board (PCB) material should be a dielectric that does not allow significant stray current leakage and at the same time the conductivity of it should provide the rapid relaxation of the space charges and the breakdown phenomena exclusion. In [3,7] a series of experimental works had been conducted which resulted in information about eliminating space charge accumulation in such a dielectric.

Fig. 1 shows the curves of the dielectric charging by a flux of electrons coming from the space plasma. An electric conductivity of the dielectric for curve 1 is 10^{-12} $Ohm^{-1}m^{-1}$, for curve 2 – 10^{-11} $Ohm^{-1}m^{-1}$ and curve 3 – 10^{-10} $Ohm^{-1}m^{-1}$. Fig. 2 shows an electric field in the dielectric as a function of time. The dashed line indicates the field value for discharge initiation. These figures show that the selection of material with high dielectric conductivity allows avoiding an accumulation of a critical charge required to cause discharge (curve 3).

As a result, it has been established that by introducing conductive carbon particles into the dielectric with required properties are enough for eliminating space charge accumulation, and revealed that the increased conductivity does not degrade the device characteristics.

Consequently, studies have shown that the use of such dielectrics eliminates the possibility of ESD, including the internal ones, as well as the bulk charging of dielectrics used

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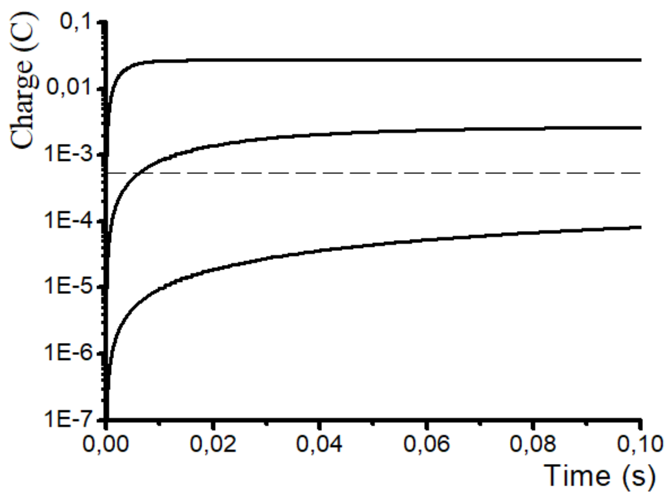

Fig. 1. The temporal dependence of the dielectric bulk charging under electron irradiation.

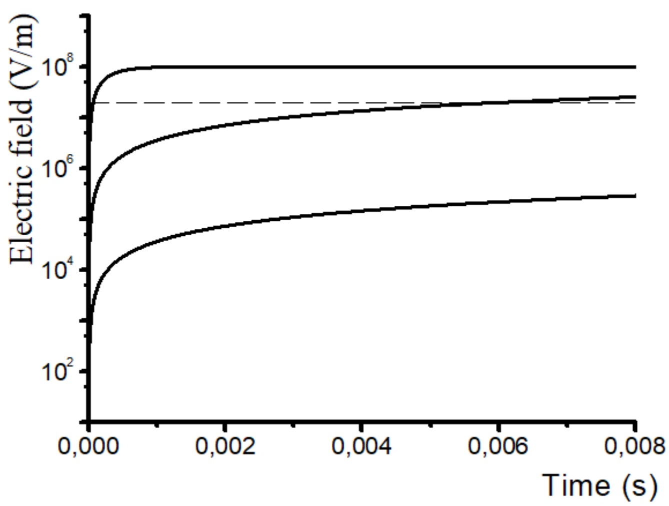

Fig. 2. The temporal dependence of the electric field in the dielectric under electron irradiation.

in the circuitry of the onboard electronic equipment. The use of such material for SC equipment in the long term would allow to increase their reliability and to increase the active lifetime.

III. The calculation of the integrity in of a microstrip line with a nanoconducting dielectric

In presently used digital devices, the binary signals have the rise time of less than 0.2 ns, and analog attributes caused by the complex interaction of numerous elements of the scheme, from the output parameters of the driver to coordinate routes of transmission of the signals. The extension of the frequency range amplifies the manifestations of physical causes of signals failure such as skin effect and dielectric losses.

However, to prove the possibility of application of these materials in transmission lines, including those operating in the microwave range it is necessary to evaluate the signal integrity (SI) of the microstrip transmission lines using nanoconducting dielectric substrates.

Signal distortion is much more pronounced at high frequencies than at low ones. This circumstance leads to the shape changing of the pulses transmitted over the transmission lines. Such distortion of the signals occurs in the result of conductivity frequency dispersion of the conductors transmission lines (skin effect) and because of the frequency dependence of the dielectric loss factor. Both circumstances lead to a breach of the SI and the shape of the transmitted pulses for the following reason. One can imagine a sequence of rectangular pulses as a sum of the Fourier transform harmonics with different frequencies. For harmonics with low frequencies, the decrease of the conductivity of the transmission line conductors due to skin effect has almost no effect. However, for harmonics with high frequencies a reduction of the conductivity of the transmission line conductors is quite noticeable. Therefore, the initial pulse of the transmitted sequence and the pulses obtained through the inverse Fourier transformation on the output of the transmission line will be different so that the SI will be broken. A similar situation occurs with the frequency dependence of the loss factor of the dielectric transmission line [8]. The cited paper described the work that examined the influence of skin effect and dielectric losses on the SI in a copper microstrip transmission line made on the substrate of nanoconducting dielectric with specified relative permittivity, loss factor and conductivity.

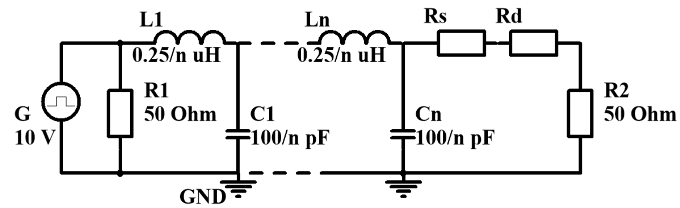

Fig. 3. The equivalent circuit of the microstrip line.

It should be noted that the focus is on the influence of the properties of radio materials on the SI. The work does not cover any additional distortion of the signals associated with the parasitic capacitive and inductive connections, resonance phenomena and reflections at discontinuities of the transmission line.

When considering the skin effect for calculating the thickness of the conductive layer, we introduce a parameter δ, which is defined as the depth at which the current density decreases e times in comparison with the current density on the conductor surface.

Conductor resistance of microstrip line in this case will be determined as:

$$R_s = \rho \frac{l}{w\delta} \quad (1)$$

where

w the width of the strip;

ρ electric resistivity of the conductor metal (copper) taken equal to $1.8 \cdot 10^{-8}$ Ohm·m;

l the length of the microstrip line.

Parameters of microstrip line with a characteristic impedance R = 50 Ohm were selected as follows: width of strip w = 5.2 mm, substrate thickness h = 2.5 mm, the

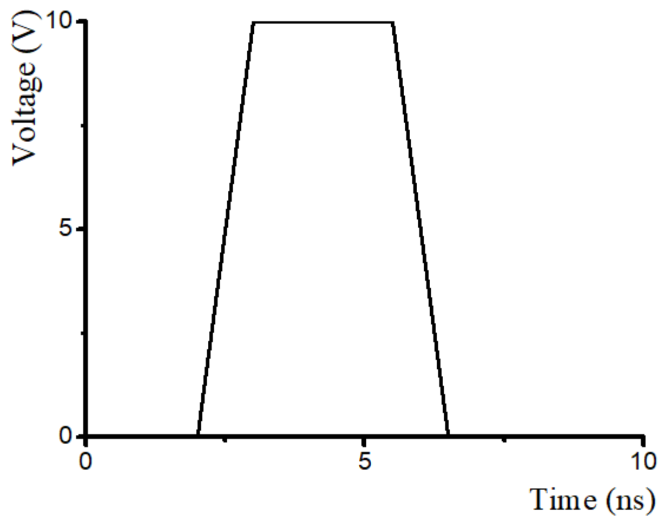

Fig. 4. The original signal.

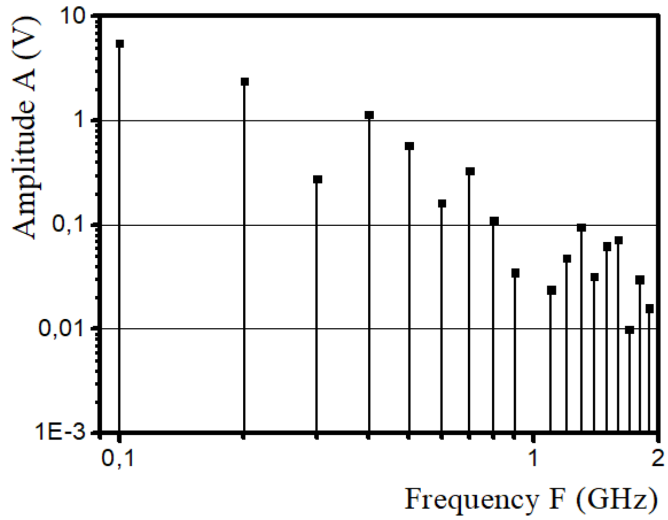

Fig. 5. Amplitude and frequency of the harmonics of the direct Fourier transform of the test pulse.

dielectric permittivity of a substrate ε = 2.5.

The equivalent circuit that was used in the simulation of propagation of a test pulse through microstrip lines is presented in Fig 3. Here G - test pulse generator, Rser=50 Ohms is the internal resistance of the generator, L1...Ln, C1...Cn - equivalent inductance and capacitance of the microstrip line, R1=50 Ohms coherent load resistor, Rd is the equivalent resistance of the frequency dependent losses in the dielectric, Rs is the equivalent frequency dependent resistance of the resistive losses in the conductors of the microstrip line.

Rd was taken equal to zero in the calculations to account for losses only to the skin effect. The resistor Rs was set to zero in the calculations to account for losses only in the dielectric resistance. Both Rd and Rs were different from zero in the calculations considering the full losses.

As a test pulse from the generator G used a pulse amplitude of 10 V, shown in Fig 4. It was conducted by direct Fourier transformation to assess the impact of skin effect on this test pulse as it moves across the microstrip line. The signal was decomposed into 20 harmonics with the frequencies and

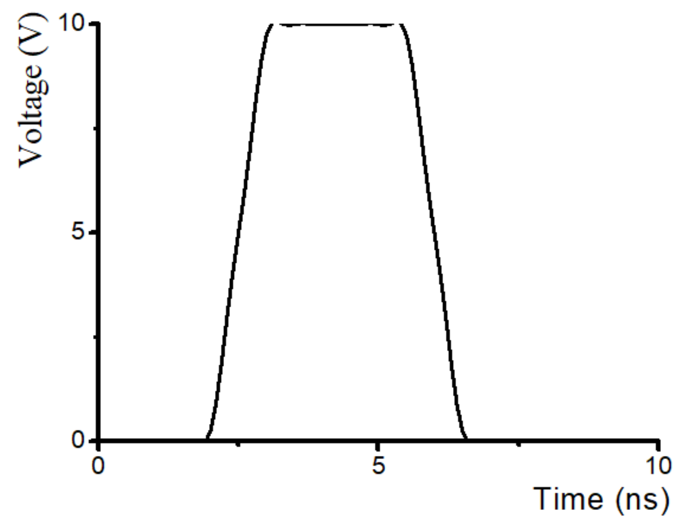

Fig. 6. The convolution signal without distortion.

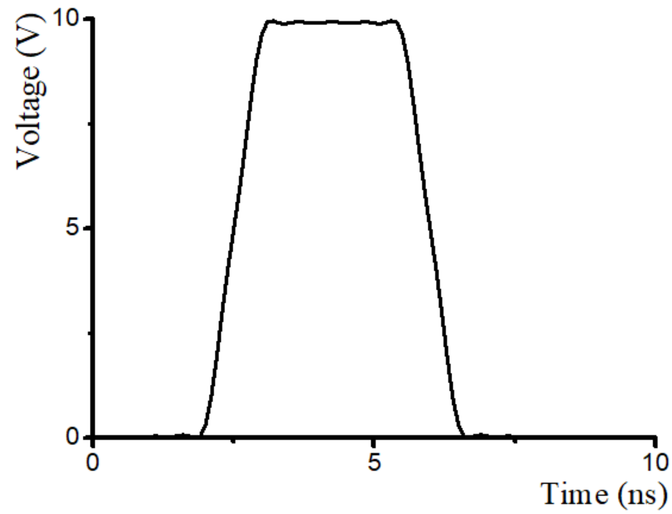

Fig. 7. The pulse at the output of the line (distortion due to skin effect).

amplitudes shown in Fig. 5 where A is the amplitude of the harmonic and F is the frequency. Using this equivalent circuit, we calculated the losses caused by skin effect for each of the 20 harmonics of a direct Fourier transform. The losses for each harmonic were calculated by the voltage drop in the circuit with a resistor, to simulate the increase of transmission line resistance Rs with the frequency, by reducing the thickness of the skin layer δ for a copper conductor as:

$$\delta = 66 \cdot 10^{-3} \sqrt{\frac{1}{F}} \tag{2}$$

where F is the frequency of the signal.

Thus, losses are determined by the following formula:

$$U_{loss} = I \cdot R_s \tag{3}$$

where

I the current in a coherent line;

Rs the conductor resistance.

Then, the inverse Fourier transformation was performed on these 20 harmonics - decomposition after taking into account the decrease in amplitudes. Fig. 6 shows the convolution

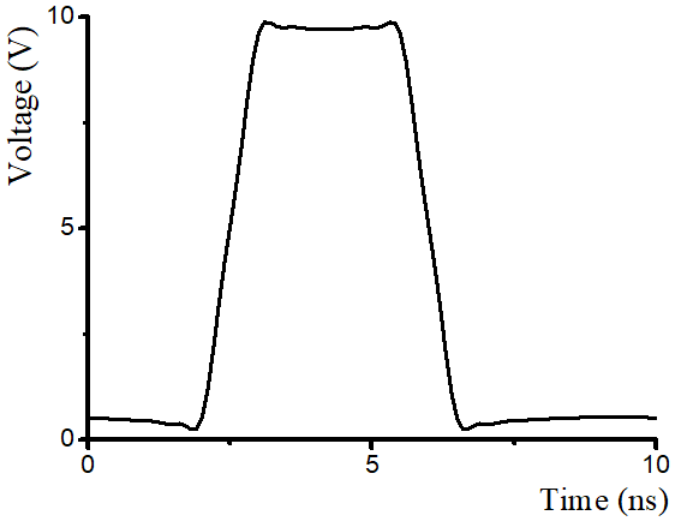

Fig. 8. The pulse at the output of the line (distortions due to dielectric loss).

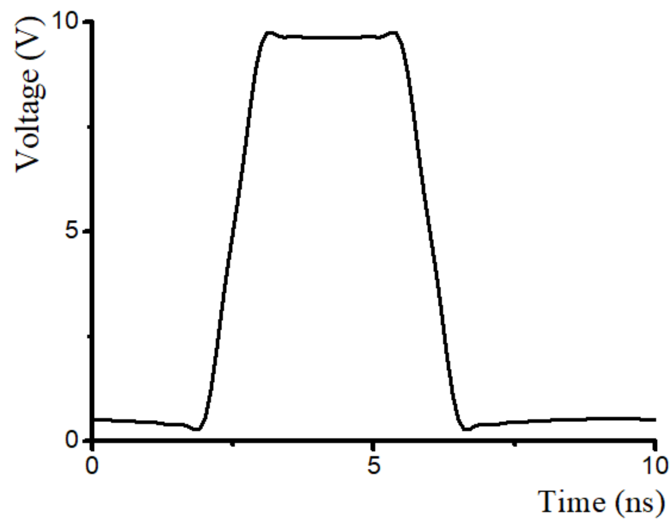

Fig. 9. The pulse at the output of the line (distortions due to total losses).

signal, to which no distortion was applied. Fig. 7 shows the convolution signal for a probe pulse at the output of a 1 m long microstrip line. This pulse was calculated only considering the losses due to the skin effect.

The resistance was represented by the equivalent sum of the losses through conduction and active polarization loss in the dielectric in the calculation of dielectric loss. It represents the ratio of the loss factor to the product of the capacitance of the dielectric and the angular frequency of the signal. The loss factor has been measured [9] in the frequency range from 100 Hz to 1 MHz. The experimental frequency dependence of the loss factor for selected concentration of conductive filler (parts of soot) of 7%. This concentration of the conductive filler provides the desired value of an electrical conductivity sufficient for exclusion of the ESD.

Fig. 8 illustrates the convolution signal to a test pulse, which was obtained by calculation considering only the losses in the dielectric for a line length of 1m.

Fig. 9 shows the convolution of the signal with consideration of losses from skin effect and dielectric loss.

It might be seen from the figures that distortion of the test pulse due to the skin effect and dielectric loss is negligible for a such microstrip line. Signs of the signal integrity violation in microstrip line with a nanoconducting dielectric (conductivity of which is about 10^{-9} $Ohm^{-1}m^{-1}$) were not observed.

IV. Conclusion

The results of computer simulations performed in this work allow to recommend using of nanoconducting dielectrics as substrates of pulse devices and microwave analog circuits designed for SC onboard avionics application. The use of these substrates allows excluding the possibility of ESD occurrence on SC operating at the geostationary orbit, highly elliptical orbits and in the auroral regions of the Earth's magnetosphere. At the same time, the increased conductivity of these substrates does not affect the integrity of the transmitted signals.

Acknowledgment

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