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Optimization of Protective Varnish Thickness to Minimize Crosstalk in Multiconductor Bus of Spacecraft PCB

Roman S. Surovtsev, Talgat R. Gazizov

***Abstract*— The paper presents the results of optimal choice for the protective varnish thickness to minimize crosstalk in multiconductor bus of a spacecraft printed circuit board. The study of situations with various resistances at the bus ends has been performed: a situation close to matching (all resistances equal to 50 Ω), mismatch at the end (resistances equal to 50 Ω at the beginning of the bus, and to 1 MΩ – at the end), full mismatch (resistances equal to 5 Ω at the beginning of the bus, and to 1 MΩ – at the end). As a result, it was found that in the situation of full mismatch, due to the simple increase of the varnish layer thickness, it is possible to reduce the amplitude of the near-end crosstalk of the bus; and by choosing the optimum thickness value of the varnish layer, the amplitude of the far-end crosstalk can be reduced almost by half.**

***Index Terms*—electromagnetic compatibility, crosstalk, protective varnish**

I. INTRODUCTION

NOWADAYS radio electronic equipment (EE) is widely used in almost all spheres of human activity. Therefore, the correct and uninterrupted work of EE underlies the safety of each person and of modern society in general. In this regard, one of the urgent tasks of designing EE is to provide electromagnetic compatibility (EMC) of critical systems, specifically, on-board equipment of a spacecraft. This results from the complex electromagnetic environment of the orbit, the use of the unpressurised enclosure together with the high circuit density and the increase of the spectrum upper frequency limit of signals used. The solution of new tasks requires increasing the number of the spacecrafts simultaneously operating on the Earth's orbit and increasing their active shelf life. For example, the Global Navigation Satellite System requires 24 simultaneously operating spacecrafts.

To ensure EMC of spacecraft equipment, there are performed system tests under the conditions of severe electromagnetic environment [1]. It is recommended to carry out these tests in frequency range up to 1, 18, 20 and 100 GHz [2–5]. The traditional means of EMC assurance are electromagnetic shields, but their effectiveness is negatively affected by the enclosure and aperture resonance at high frequencies. In this case, high-frequency electromagnetic interference, bypassing the shields, can penetrate into EE and, due to high field density, disable low-frequency circuits of the on-board EE. Besides the reduction of protective effectiveness, additional shielding leads to the increase of the spacecraft weight and, hence, the cost of its placement into orbit. Finally, if the tests revealed incompliance with the requirements, it is not always evident what changes in the design of the printed circuit board (PCB) and electrical circuits are necessary to make to guarantee success in the repeated tests [6]. This leads to the relevance for repeated testing, which results in additional costs. The solution of this problem lies in simulating the system and assurance of EMC at the stage of designing spacecraft equipment.

At the spacecraft PCB design stage, developers must solve problems of signal integrity. As for spacecraft equipment, it is worth mentioning thematic issues of the leading EMC journal – *IEEE Transactions on EMC*. The issues devoted to aerospace EMC [7], signal integrity, power integrity and EMC at the PCB level [8] are of a great current interest. In the context of signal integrity assurance, special attention is given to crosstalk in the PCB interconnections since exceeding the level of acceptable crosstalk degrades the internal system electromagnetic environment, and can lead to the spacecraft malfunction or loss.

There are many approaches to decrease or cancel crosstalk in the PCB interconnections. For example, there are some approaches to reduce crosstalk in the pair of coupled microstrip lines by means of a defected conductor [9] and a step-shaped conductor [10]. There are also efforts to reduce interference in multiconductor lines due to making changes in dielectric filling parameters [11], including anisotropic one [12]. One of the approaches to cancel crosstalk is interesting because it is based on mounting a guard trace between the signal conductors [13–15]. It is important to note the results of simulating a coupled line with a guarded trace grounded at one end and with open circuit at the other, as the crosstalk reduction there is shown to be more than 50% [15]. In a pair of connected long length lines, the far-end crosstalk has greater amplitude compared to the near-end, so the far-end crosstalk cancellation gained more attention [16–21]. It is worth mentioning the research into the dependence of the level

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of far-end crosstalk in the coupled four-conductor transmission line (with zero loads at the beginning of the line and matched at the end) on the thickness of the additional dielectric layer and the line length [22]. But all these studies were carried out on the simple idealized structure examples but not on a real spacecraft PCB. In addition, in these investigations the emphasis is placed only on the far-end crosstalk.

The aim of this paper is to assess the possibility for choosing the optimal thickness of a protective varnish to minimize the crosstalk level in multiconductor interconnection of a spacecraft PCB.

II. INITIAL DATA FOR SIMULATION

For the research, we chose an eight-conductor bus on the Bottom layer of a real spacecraft PCB with the length *l* of 74 mm (Fig. 1).

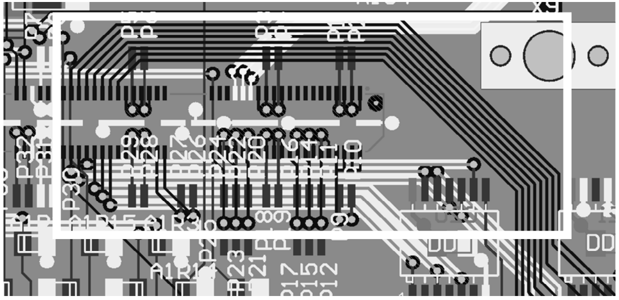

Fig. 1. Eight-conductor bus on the Bottom layer of a spacecraft PCB

The PCB cross-section is shown in Fig. 2. It consists of the following layers (relative dielectric permittivity is given for the frequency of 1 GHz): IS420ML fiberglass (h_4=0.2 mm, ε_{r4}=4.9), IS420ML1080 prepreg (h_3=0.1446 mm, ε_{r3}=4.49), solder resist (h_2=20 µm, ε_{r5}=3.5), and EP 730 protective varnish ($h_1\approx3\times20$ µm, ε_{r1}=3.5–5). The thickness of the foil on Top and Bottom layers t_1 is 65 µm, the thickness of the foil on Mid 1, Mid 2, Power and Ground layers t_2 is 35 µm.

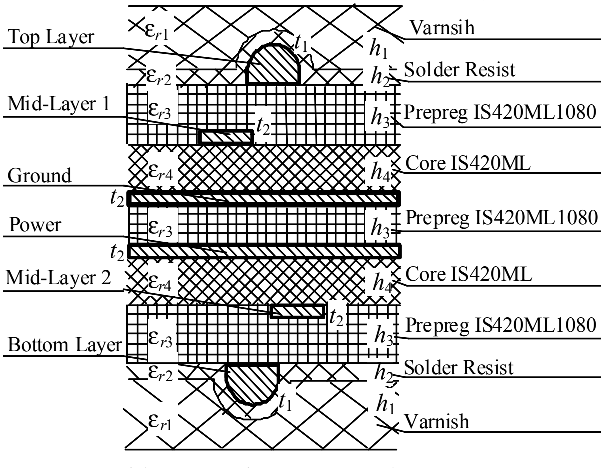

Fig. 2. Fragment of the spacecraft PCB cross-section

To simulate the PCB we chose the simplest case, when the protective varnish covers the entire bus surface. Fig. 3 shows the fragment of the geometric model of the bus cross-section performed in TALGAT software [23]. The width of the conductor base (*w*) is 300 µm, and the space between the conductors (*s*) is 320 µm.

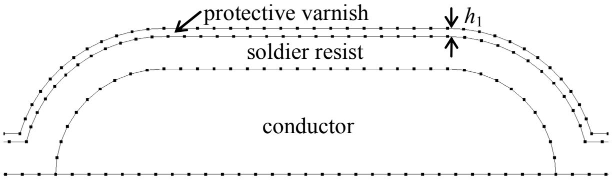

Fig. 3. Cross-section fragment of the bus obtained with TALGAT software

To evaluate the impact of the protective varnish layer thickness on the crosstalk level, we performed the calculation of waveforms at the ends of passive conductors. The exciting pulse has a trapezoid shape with parameters: e.m.f. amplitude is 6 V, duration of the flat top is 8 ns, and the rise and fall durations are 1 ns each. For clarity, the circuit diagram of the bus is shown in Fig. 4.

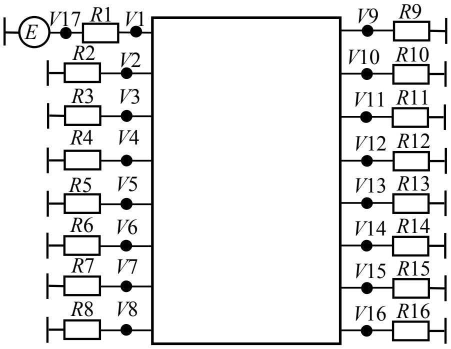

Fig. 4. Circuit diagram of the bus

III. QUASISTATIC SIMULATION OF THE BUS

First and foremost, the evaluation of crosstalk level is desirable for various matching modes, since for the mismatched bus the resulting signal at the bus ends is defined by superposition of incident and reflected waves of each mode of a multiconductor line. Essentially, all induced signals in the event of mismatching will be close to the sum of the near- and far-end crosstalk in the matching mode. The following matching modes are considered: a case close to the matching mode (all resistances are 50 Ω), mismatch at the end (resistances are 50 Ω at the beginning of the bus, and 1 MΩ – at the end), full mismatch (resistances are 5 Ω at the beginning of the bus, and 1 MΩ – at the end).

A. Simulation with 50 Ω loads

We performed the bus simulation with 50 Ω loads ($R1=R2=\ldots=R16$=50 Ω). The first case is the situation when only one conductor is active (outer) and the other conductors are passive. The dependence of the maximum (over all ends of the bus) crosstalk amplitude on h_1 changing in the range of 5, 10, …, 200 µm is given in Fig. 5.

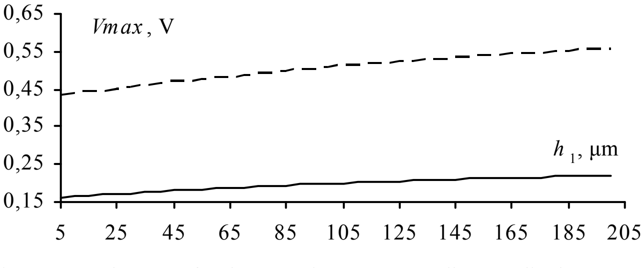

Fig. 5. Dependence of the maximum crosstalk amplitude on h_1 for N_{ACT}=1 (—) and N_{ACT}=7 (– –)

It is seen that the maximum crosstalk amplitude increases from 0.16 V to 0.22 V (by 40%) in the range of h_1, and its maximum level is about 3.5% of the e.m.f. level. As an example, Fig. 6 shows the crosstalk waveforms at the near end of passive conductors (the first three from the active conductor) for the extremities of h_1 variation range.

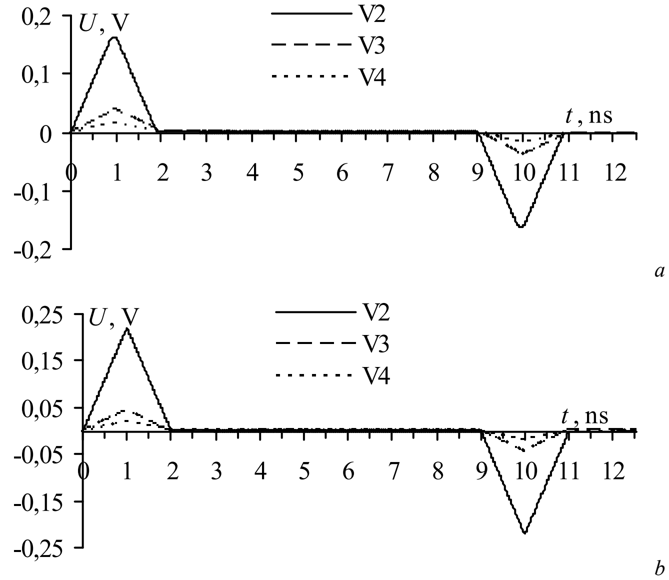

Fig. 6. Near-end crosstalk waveforms for l=74 mm, h_1=5 (*a*) and 200 µm (*b*)

The far-end crosstalk waveforms for a number of values of h_1 are shown in Fig. 7. It is seen, that they behave differently: the crosstalk level on the nearest conductor decreases by 10 times, and then (when h_1 passes from 100 µm to 120 µm) it changes the polarity, and increases to 0.02 V at h_1=200 µm.

A similar simulation was performed for all possible influences on the bus. At first, the source was successively moved along conductors 2–4 (the remaining cases were not considered because they are mirror-like), and then the number of active conductors was successively increased to 2, 3, 4, 5, 6 and 7, and they were moved over all bus conductors. Summary results for the situation when all conductors are active except central one (N_{ACT}=7) are shown in Fig. 5. From the obtained results, it can be seen that the crosstalk amplitude increases by 2.5–2.65 times in h_1 variation range and can be 5–17% of the signal amplitude in the active conductor and the increase of h_1 results in the 30% increase of crosstalk amplitude.

Then, we evaluated how the increase of the line length (l=150, 225, 300 mm) impacts the crosstalk waveform and amplitude. As the result, we observed a weak increase of the near-end crosstalk amplitude and duration which was proportional to bus length (Fig. 8).

For far-end crosstalk, with the increase of l we observed the amplitude increase up to 0.13 V (8.7% of the signal in the active conductor) and the increase of signal step duration caused by the reflection from the far-end of the bus (Fig. 9*a*). The increase of the protective varnish layer thickness reduces the crosstalk level to 0.05 V (3.3% of the level in the active conductor) and changes its polarity (Fig. 9b).

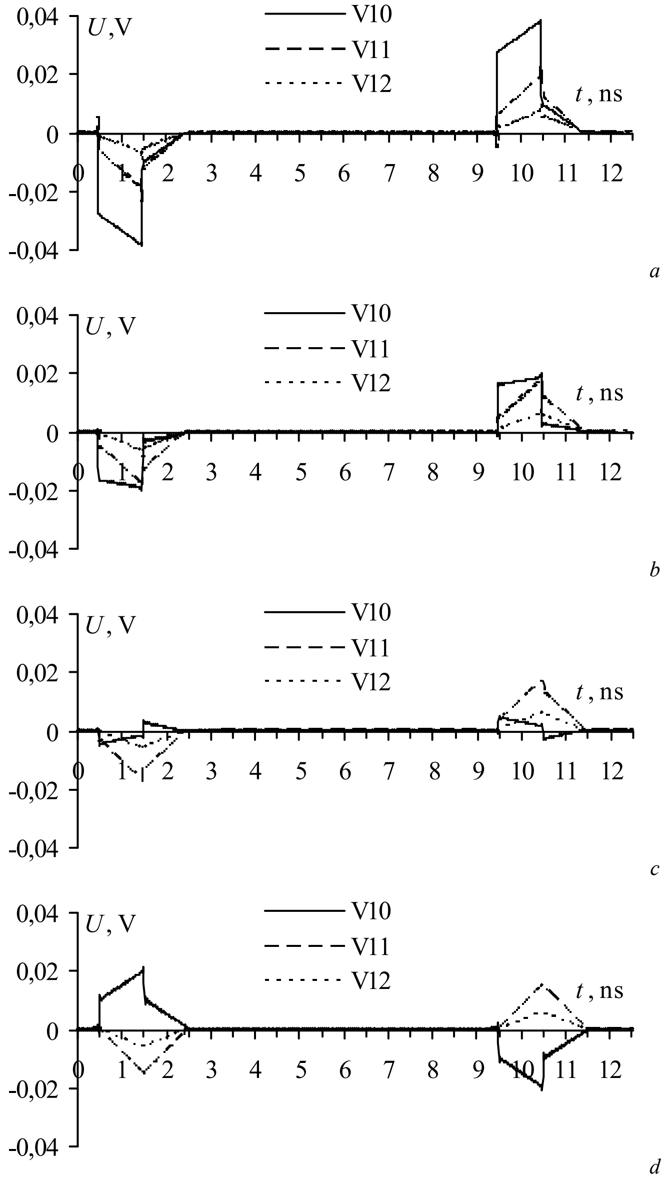

Fig. 7. Far-end crosstalk waveforms for l=74 mm, h_1=5, 50, 100, 200 µm (*a-d*)

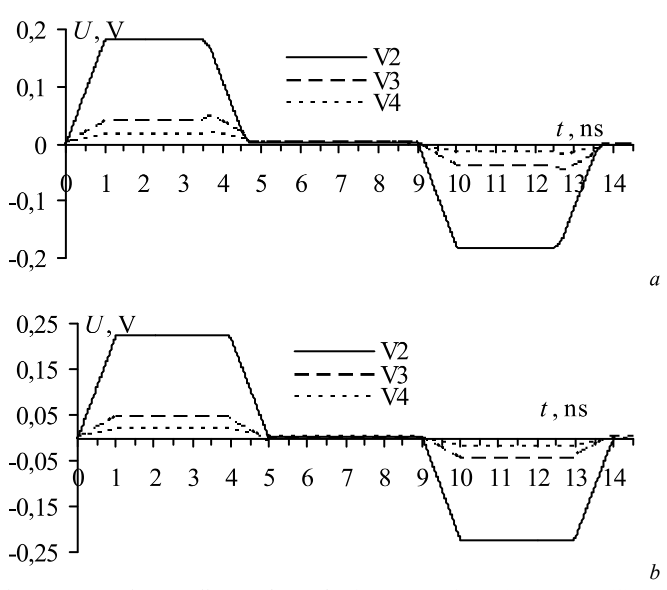

Fig. 8. Near-end crosstalk waveforms for l=300 mm, h_1= 5 (*a*), 200 µm (*b*)

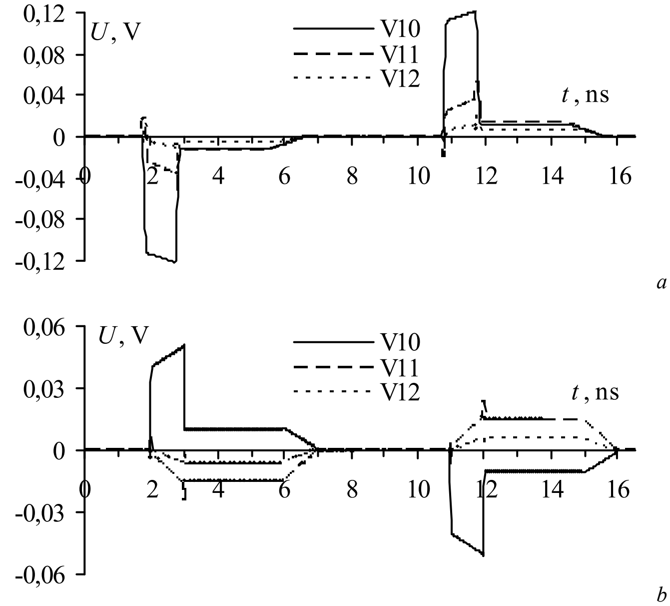

Fig. 9. Far-end crosstalk waveforms for l=300 mm, h_1= 5 (*a*), 200 µm (*b*)

B. Simulation with 50 Ω at near-end and 1 MΩ at far-end

We performed the bus simulation with mismatching at the far-end ($R1$=$R2$=…=$R8$=50 Ω, $R9$=$R10$=…=$R16$=1 MΩ) (Fig. 10, 11).

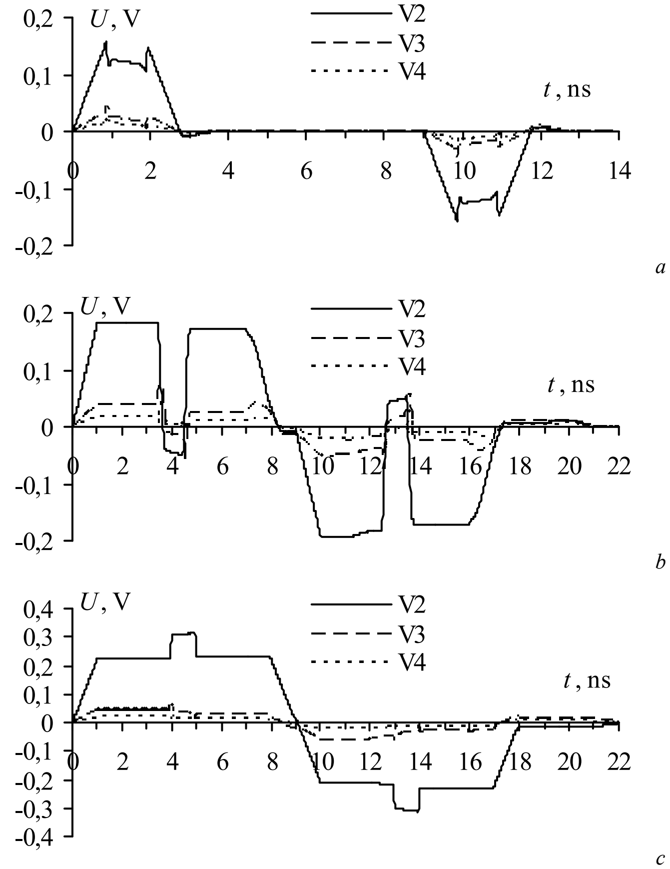

Fig. 10. Near-end crosstalk waveforms for h_1=5 µm and l=75 mm (*a*), l=300 mm (*b*) and h_1=200 µm, l=300 mm (*c*)

For the near-end crosstalk with minimal protective varnish thickness, a signal dip of 0.03 V is observed (2% of the signal in the active conductor) for l=75 mm and of 0.23 V (15% of the signal in the active conductor) for l=300 mm. The dip can be explained by the summation of two signal components: near-end crosstalk and crosstalk from the signal reflected from the far-end of the bus (Fig. 10*a*, *b*). The increase of the protective varnish thickness results in changing the polarity of a crosstalk component from the far-end reflected signal, thus increasing the peak value of the total signal to 0.32 V (21% of the signal in the active conductor) for the length of 300 mm and the layer thickness of 200 µm (Fig. 10*c*).

For the far-end crosstalk, the summation of two signal components is also observed: far-end crosstalk with the crosstalk from the signal reflected from the far-end of the bus (Fig. 12*a*). The increase of the bus length (from 75 to 300 mm) leads to an insignificant increase of the amplitude and the duration of the sum of these components (Fig. 11*a*, *b*). The increase of the protective varnish thickness leads to the increase of the components total peak value up to 0.53 V (35% of the signal in the active conductor) (Fig. 12*c*).

Thus, the mismatch at the far-end leads to the increase in the peak value of the crosstalk amplitudes at the near- and far-ends to 0.32 V and 0.53 V, respectively.

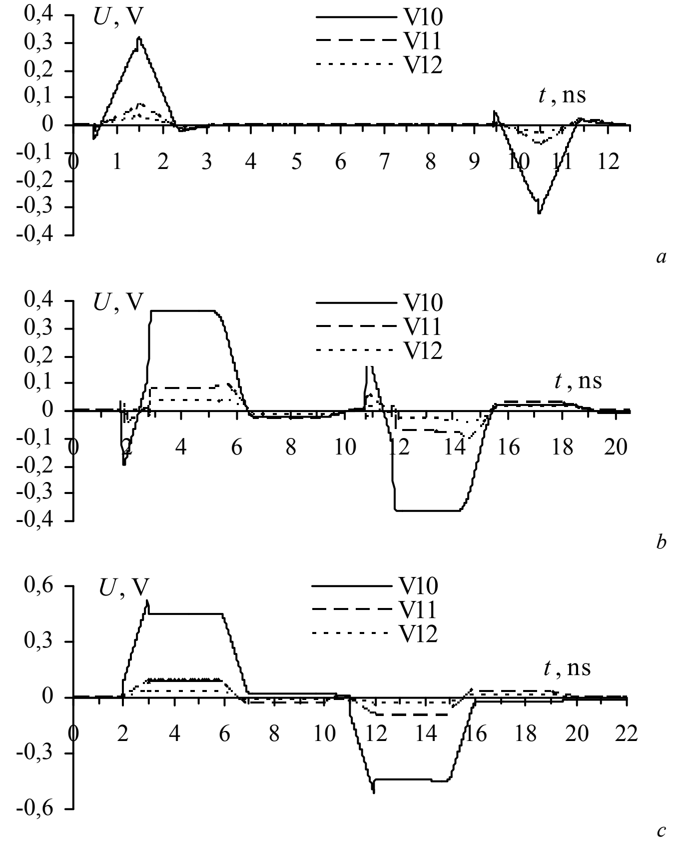

Fig. 11. Far-end crosstalk waveforms for h_1=5 µm, l=75 mm (*a*), l=300 mm (*b*) and h_1=200 µm, l=300 mm (*c*)

C. Simulation with 5 Ω at near-end and 1 MΩ at far-end

We performed the bus simulation with a full mismatching ($R1$=$R2$= ... =$R8$=5 Ω, $R9$=$R10$= ... =$R16$ =1 MΩ), which imitates a small output resistance of the driver and a high input resistance of the receiver. At the near-end, we observed the oscillations with the amplitude up to 0.05 V (less than 2% of the level in the active conductor) for l=75 mm and 0.2 V

(6.6% from the signal in the active conductor) for *l*=300 mm (Fig. 12*a*, *b*). The increase of the protective varnish thickness leads to the reduction of the near-end signal amplitude to 0.1 V (3.3% from the signal in the active conductor) for *l*=300 mm and the varnish layer thickness of 200 µm (Fig. 12*c*).

The oscillations are also observed for far-end crosstalk. With the increase of the bus length (from 75 to 300 mm), we observed a serious increase in amplitude (from 0.55 to 1.9 V, which is 18 and 63% of the level in the active conductor) and the signal duration (Fig. 13). The increase of the protective varnish thickness to 100 µm leads to the decrease of the crosstalk amplitude to 0.75 V (25% of the level in the active conductor) (Fig. 14*a*), and its further increase to 200 µm leads to signal amplitude increase to 1.2 V (40% of the level in the active conductor) (Fig. 14*b*).

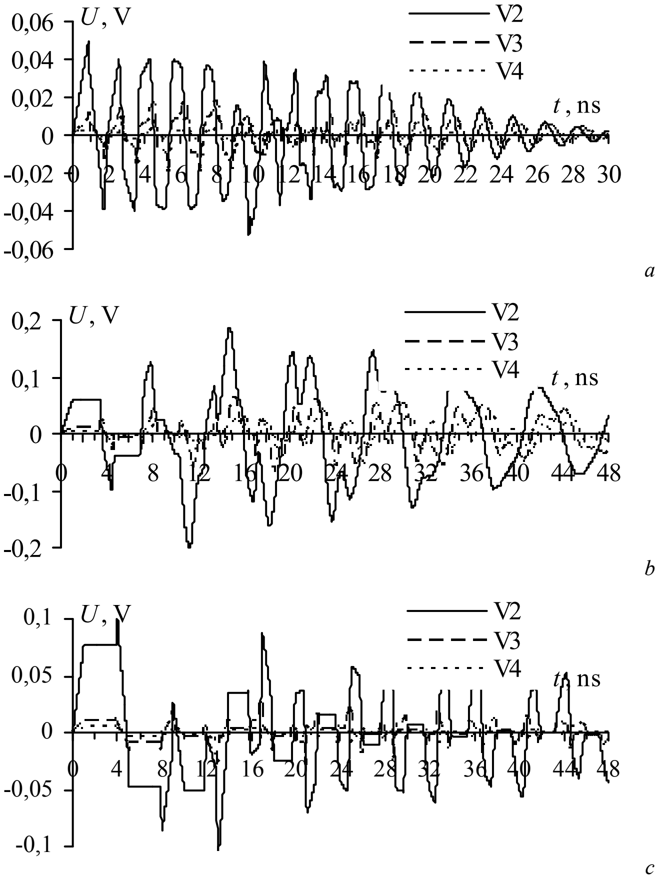

Fig. 12 Near-end crosstalk waveforms for h_1=5 µm, *l*=75 mm (*a*), *l*=300 mm (*b*) and h_1=200 µm, *l*=300 mm (*c*)

Thus, in case of a full mismatch, the crosstalk amplitude at the near-end of the line is small (up to 0.1 V), and at the far-end it is large (up to 2 V). By increasing the protective varnish thickness, it is possible to reduce the amplitude of the near-end crosstalk. By choosing the optimum thickness value of the varnish layer, the amplitude of the far-end crosstalk can be reduced almost by half. This suggests that there is a simple way to reduce the crosstalk level without changing the PCB layout and introducing additional components, namely, by choosing the optimal thickness of the protective varnish coating at the latest stage of the PCB assembly.

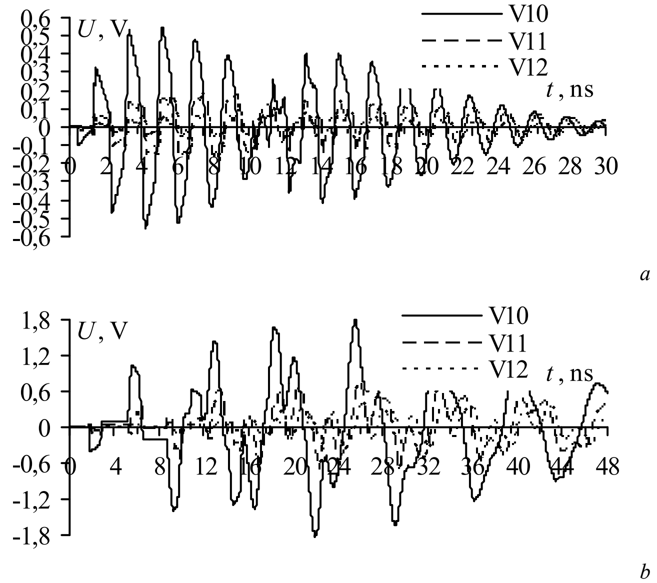

Fig. 13. Far-end crosstalk waveforms for h_1=5 µm, *l*=75 (*a*) and 300 (*b*) mm

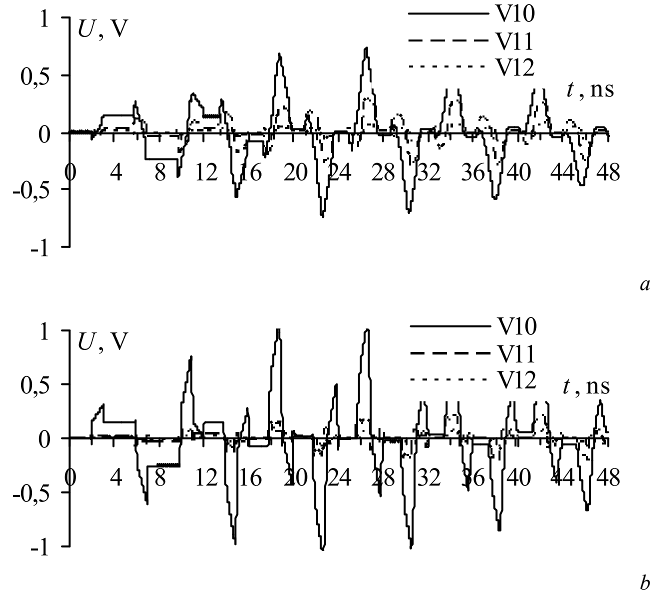

Fig. 14. Far-end crosstalk waveforms for *l*=300 mm, h_1=100 (*a*) and 200 µm (*b*)

IV. CONCLUSION

The task of minimizing crosstalk in multiconductor interconnects by means of coating PCB with the protective varnish is quite difficult, and its solution requires conducting complex studies. The main part of them is a large number of computational experiments on various examples of multiconductor interconnection with various dielectric fillings and employing various PCB coating processes. In this paper, only complete protective varnish coating (when the coating layer is applied to the entire PCB surface) has been considered. The main result of the paper is that in the case of full mismatch, due to simple increase of the protective varnish layer thickness, it is possible to reduce the amplitude of the near-end crosstalk of the bus; and by choosing the optimum thickness value of the coating layer, the amplitude of the far-end crosstalk can be reduced almost by half. The simulation results show the possibility to develop the technique of applying protective coating with optimal thickness to reduce the crosstalk amplitude and to improve EMC.

At the same time, other techniques of applying protective varnish coating remain unexplored: coating only critical interconnects along their entire length; coating only critical sections along an interconnect along its entire width; coating only critical sections along the length and width of an interconnect. The mentioned techniques of applying protective varnish are more difficult to implement in comparison with the considered one, but can be more effective due to the selective rather than complete interconnection coating. Thus, to solve the task of improving EMC by applying PCB coating with an optimal thickness, it is necessary to carry out a large number of computational experiments, detailed analysis and systematization of the results. The next step is a series of full-scale experiments, which will allow us to confirm the feasibility of the technique and to develop the technology for reducing crosstalk with PCB coating as well.

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