Additional Pulses in the Time Response of a Modal Filter with a Passive Conductor in the Reference Plane Cutout

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Abstract – **The paper considers the technique for improving the protection against an ultrashort pulse with the help of a modal filter made by cutting a passive conductor in the reference plane of a microstrip line. The influence of the asymmetry of the cross section on the difference between the mode delays and the amplitudes of the decomposition pulses is studied. The decomposition of the first and second pulses, which merged at symmetry, is achieved. The appearance of additional pulses was revealed. It is shown that the delays of additional pulses are determined by a linear combination of the per-unit-length delays of the line multiplied by its length. The influence of boundary conditions at the ends of a passive conductor with an asymmetric structure is investigated. The appearance of additional pulses was detected, the amplitude of which is greater than the amplitude of the pulses of three main modes. The optimum value of separation between the conductors is obtained, which gives the attenuation by 10.4 times.**

Index terms – **modal filter, ultrashort pulse, electronic equipment, protection device, microstrip line.**

I. INTRODUCTION

THE PROBLEM OF ENSURING electromagnetic compatibility is becoming increasingly relevant. This is due to the widespread penetration of computer and telecommunication systems into various spheres of human activity, the expansion of the frequency range due to the emergence of new communication systems, the increase in the speed of information processing systems, and the stricter requirements for the immunity of electromagnetic devices to the effects of various electromagnetic radiation, including ultrashort pulses (USP) of high power. Conventional protection devices (filters, isolation devices, noise suppressors, discharge devices and others) are not able to effectively protect against USP [1]. They have large dimensions, high cost, as well as low radiation resistance due to the presence of semiconductor elements. Therefore, the search for new protection devices is relevant. An overview of protection devices is given in article [2].

II. PROBLEM STATEMENT

A new, small-sized and cheap to implement, means of protection against a USP is a modal filter (MF), in which the USP is decomposed into pulses of lower amplitude due to different per-unit-length delays of signal modes in a coupled line with an inhomogeneous dielectric filling. However, all MFs require a passive conductor, which degrades their overall dimensions [3-7]. Meanwhile, this drawback can be eliminated by cutting out the passive conductor in the reference plane of the microstrip line [2]. For the symmetric structure of such an MF, alignment of the pulse amplitudes at the output is achieved. In this case, the per-unit-length delays of the two fast modes are very close (with a difference of 0.01 ns/m), which forms one pulse at the MF output, and the difference in the linear delays of the second and third modes is quite large (3.18 ns/m) [8]. Therefore, the aim of this paper is to study the effect of asymmetry on the difference in per-unit-length mode delays and the time response of the MF.

III. DESCRIPTION OF MF

The MF is a microstrip line with two cutouts in the ground plane, between which a passive conductor is formed. Fig. 1*a* shows the cross section of the MF where ε_r is the relative permittivity of the substrate, w_1, w_2, w_3 are the widths of the conductors, t is the thickness of the conductors, h is the thickness of the substrate, s is the separation of the conductors. We chose foiled fiberglass (ε_r=4.5) as a substrate material because of its cheapness, accessibility, and widespread use.

The MF connection diagram circuit is shown in Fig. 1*b*. The active conductor is connected to a pulse signal source represented on the circuit as an ideal e.m.f. source E and internal resistance $R1$. At the other end, the active conductor is connected to the load $R4$. The resistance values $R1$, $R2$, $R4$, $R5$ are assumed to be the same and equal to 50 Ω, and for connecting the extreme conductors $R3$=$R6$=1 mΩ. The input excitation is a trapezoidal pulse with the following parameters: e.m.f. amplitude – 2 V, rise time – 150 ps, flat

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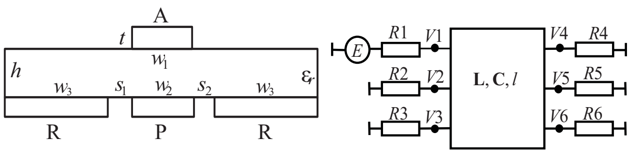
top – 200 ps, fall time – 150 ps. The calculation of the parameters and waveforms was performed using the quasistatic approach in the TALGAT system [9]. Losses in conductors and dielectrics were not taken into account.



a *b*

Fig. 1. Cross section (*a*) and connection diagram (*b*) of the MF where the conductors: R – reference, A – active, P – passive.

IV. RESULTS

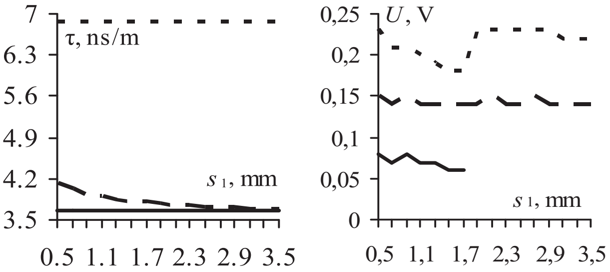
The simulation was performed with typical parameters of the foil-coated fiberglass: t=35 µm, h=0.18 mm when w_1=w_2=3.5 mm and w_3=0.5 mm.

A. Analysis of the asymmetry effects

The asymmetry was obtained by reducing s_1 from 3.5 to 0.5 mm at s_2=3.5 mm, i.e. the closer placing of one of the reference conductors. The dependences of per-unit-length delays (τ) on s_1 are shown in Fig. 2*a*. It can be seen that s_1 has the main effect on τ_2. So, with decreasing s_1, the values of τ_2 vary from 3.69 to 4.13 ns/m, and τ_1 - only from 3.65 to 3.67 ns/m. In this case, their difference ($\tau_2 - \tau_1$) increases (from 0.04 to 0.46 ns/m), and the value of τ_3 remains unchanged (6.87 ns/m).

Fig. 2*b* shows the dependences of the pulse amplitudes at the MF output. It can be seen that when s_1=1.7 mm, U_1 is interrupted and U_2 increases sharply. This is explained by the fact that the difference τ_2–τ_1 (s_1=1.7 mm) becomes small and the pulses merge with the amplitudes U_1 (0.06 V) and U_2 (0.019 V) combined. It is also seen that the amplitude of the first two modes (U_1 and U_2) becomes smaller with the increase of s_1, and U_3 changes slightly.

Fig. 3 shows examples of the results of simulating the voltage waveforms at the input and output of the MF with its length l=1 m. As it can be seen from Fig. 3*b* and Fig. 3*c,* two additional pulses of negative polarity and different delay values appear between two pulses with a triple passage along the line ($3\tau_1$ and $3\tau_2$). Fig. 3 allows drawing the conclusion that the appearance of additional pulses is affected by the asymmetry of the MF structure. Thus, for s_1=0.5 mm, there are two of them, clearly expressed (Fig. 3*c*), for s_1=1.1 mm, there is one (Fig. 3*b*), and for s_1=3.5 mm, when the MF structure is completely symmetric, there are not any (Fig. 3*a*).



a *b*

Fig. 2. Dependences of τ_1 (—), τ_2 (--), τ_3 (----) (*a*) and U_1 (—), U_2 (---), U_3 (- - -) (*b*) on s_1.

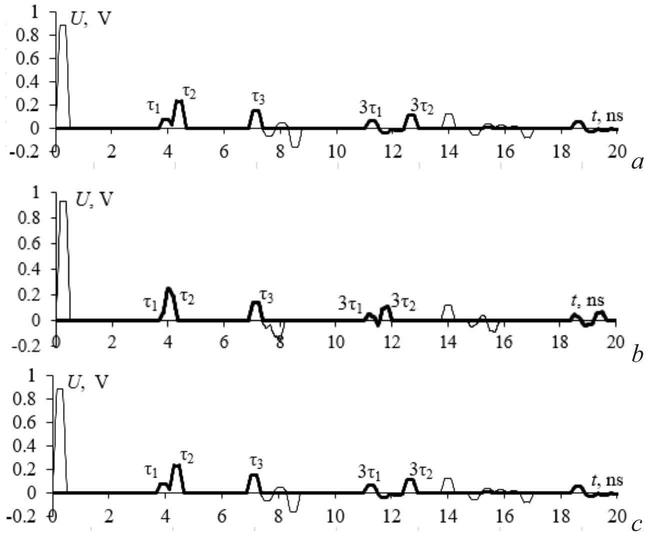


Fig. 3. Voltage waveforms of the input (-) and output (-) at the MF at s_1=3.5 (*a*), 1.1 (*b*), 0.5 mm (*c*) and l=1 m.

For a more detailed study of additional pulses, the line length was increased to 2.5 m. Tables I and II show the values of per-unit-length delays and mode arrival time. The voltage waveforms at the MF output are shown in Fig. 4. Analyzing the obtained data, we can conclude that the delays of the additional pulses are determined by a linear combination of the per-unit-length delays of the line modes multiplied by the line length. Tables III and IV show the resulting combinations and the arrival time of additional pulses 1–6. The analysis of Fig. 4 and Tables III and IV allows us to conclude that with an increase in s_1, the intervals between additional pulses and the amplitude become smaller: for s_1=0.5 mm the interval is 1.162 ns and $U1$=0.38 V, but for s_1=1.1 mm it is 0.588 ns and $U1$=0.28 V. Reducing the intervals between additional pulses and decreasing the amplitude lead to the disappearance of pulses, which is confirmed by Fig. 4*a* when they are missing at s_1=3.5 mm. It is also seen that there are 2 more of them (at 3τ there are 2 additional pulses, but at 5τ there are 4 of them), and the pulse amplitudes decrease.

TABLE I
PER-UNIT-LENGTH MODE DELAYS (NS/M)

s_1 mm	τ_1	τ_2	τ_3
3.5	3.658	3.695	6.872
1.1	3.670	3.906	6.872
0.5	3.670	4.135	6.872

TABLE II
MODE ARRIVAL TIME (NS)

s_1 mm	$\tau_1 l$	$\tau_2 l$	$\tau_3 l$	$3\tau_1 l$	$3\tau_2 l$	$3\tau_3 l$	$5\tau_1 l$	$5\tau_2 l$	$5\tau_3 l$
3.5	9.14	9.237	17.180	27.42	27.711	51.542	45.78	46.185	85.903
1.1	9.17	9.764	17.180	27.529	29.293	51.543	45.883	48.821	85.903
0.5	9.17	10.338	17.180	27.528	31.014	51.542	45.879	51.691	85.903

TABLE III
ARRIVAL TIME FOR ADDITIONAL PULSES (NS)

№	1	2	3	4	5	6
View	$3\tau_2-2\tau_1+\tau_3$	$4\tau_2-3\tau_1+\tau_3$	$3\tau_2+\tau_3$	$4\tau_2-\tau_1+\tau_3$	$5\tau_2-2\tau_1+\tau_3$	$6\tau_2-3\tau_1+\tau_3$
s_1=1.1 mm	28.120	28.708	46.473	47.061	47.649	48.237

TABLE IV
ARRIVAL TIME FOR ADDITIONAL PULSES (NS)

№	1	2	3	4	5	6
View	$2\tau_2-\tau_1+\tau_3$	$3\tau_3-2\tau_1+\tau_3$	$4\tau_2-\tau_1-\tau_3$	$3\tau_2+\tau_3$	$4\tau_2+\tau_3-\tau_1$	$5\tau_2+\tau_3-2\tau_1$
s_1=0.5 mm	28.681	29.843	47.034	48.202	49.364	50.532

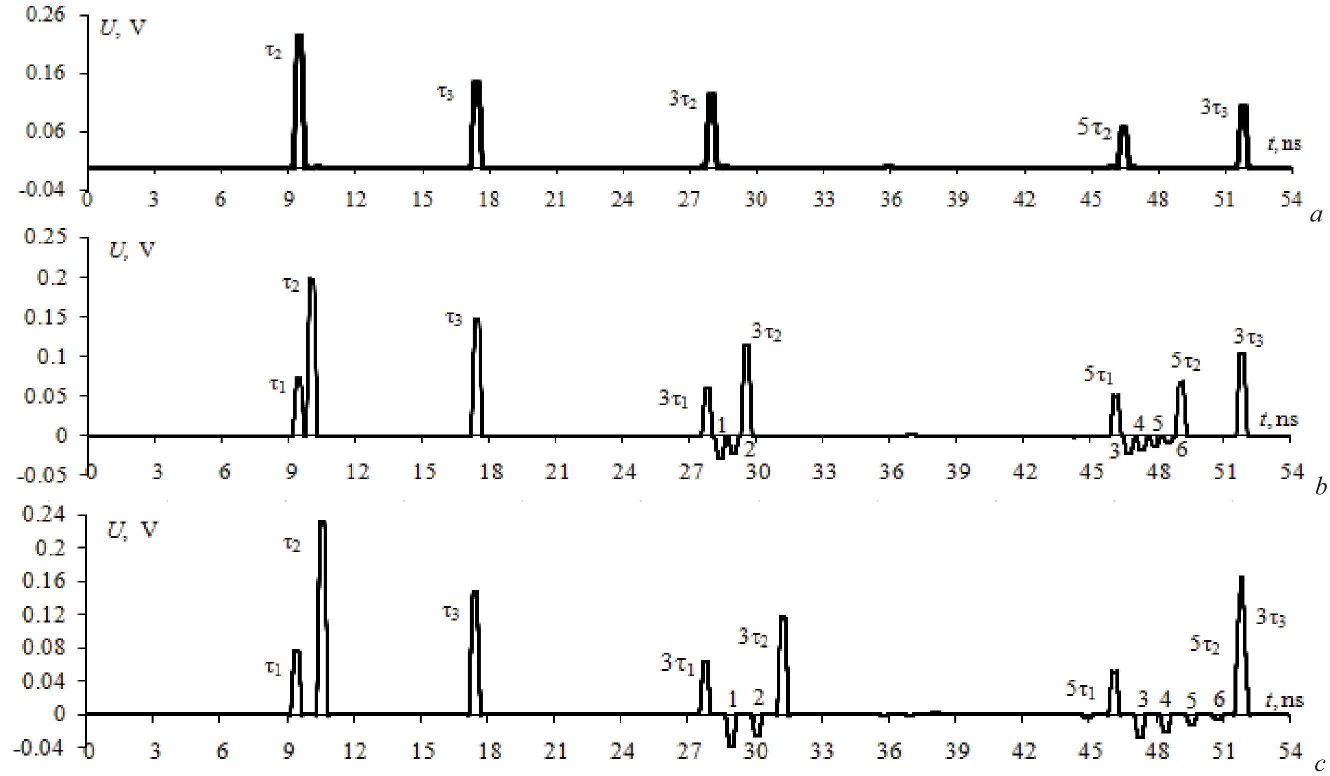


Fig. 4. Voltage waveforms at the MF input (-) and output (-) for s_1=3.5 (*a*), 1.1 (*b*), 0.5 mm (*c*) and l=2.5 m.

B. Analysis of the influence of terminations at the ends of the passive conductor

The influence of the "beginning–end" boundary conditions of the passive conductor was simulated: "short circuit (SC) – open circuit (OC)", "SC–SC", "OC–SC", "OC–OC". An SC was simulated as 10^{-3} Ω, and an OC – 10^5 Ω.

For all values of s_1 and boundary conditions of the passive conductor, the voltage waveforms were calculated, but to save the space, they are given only for "OC–SC", since the greatest attenuation (of the input signal) occurs in this case

[10]. Fig. 6 shows the results of simulating the voltage waveforms at the input and output of the MF at s_1=3.3; 1.1; 0.5 mm, respectively. Fig. 5 shows that with an increase in the asymmetry, more additional pulses appear, for s_1=3.5 mm (Fig. 6*a*) there are 2 of them, and for s_1=1.1 (Fig. 6*b*) and 0.5 mm (Fig. 6*c*) there are 4 of them. In Fig. 6*a*, 2 pulses are observed (in Fig. 6*a* they are designated as 1, 2, and in Fig. 6*b*, *c* as 2, 4), the amplitude of which is greater than the amplitude of the pulses of the three modes. Table V shows the per-unit-length mode delays. Analyzing Table V and Fig. 5, we can conclude that pulses 1 and 2 (Fig. 6*a*) and 1, 2, 3, 4 (Fig. 6*b*, *c*) are additional pulses, because they come with other delays. Fig. 6*b* and Fig. 7*c* shows that with increasing asymmetry, the distance between the additional pulses 1 and 2, as well as 3 and 4, becomes larger. Also, weakly expressed additional pulses of negative polarity appear between pulses $3\tau_1$ and $3\tau_2$ (Fig. 6*b*, *c*).

Since the attenuation of the USP at the MF output is estimated from the maximum of the amplitudes, Fig. 6 shows the dependence of the amplitude of additional pulses 2 (Fig. 6*a*) and 4 (Fig. 6*b*, *c*) on s_1, which is maximum. It can be seen that when s_1=0.5 mm, *U*2 (4) increases sharply; this is explained by the merge of pulses with the summation of amplitudes. A maximum is also observed at s_1=1.3 and 1.5 mm (*U*2(4)=0.12 V), i.e. such parameters s_1 are the worst. Then, the amplitude decreases monotonically at s_1 from 1.7 mm (*U*4=0.116 V) to 3.5 mm (*U*4=0.105 V). So, at s_1=0.7 mm, the minimum amplitude of 0.096 V was reached. The pulse merge is confirmed by Fig. 6 when there are clearly 2 pulses at s_1=3.5 mm, and 4 at s_1=1.1 and 0.5 mm.

Analyzing Fig. 5, 6 we can come to the conclusion that an increase in the asymmetry of the MF by a decrease in s_1 makes it possible to reduce the maximum amplitude to 10.4 times with respect to half the e.m.f.

TABLE V
PER-UNIT-LENGTH MODE DELAYS (NS/M)

s_1 mm	τ_1	τ_2	τ_3	$3\tau_1$	$3\tau_2$	$3\tau_3$
3.5	3.658	3.695	6.872	10.974	11.085	20.616
1.1	3.670	3.906	6.872	11.011	11.718	20.616
0.5	3.670	4.135	6.872	11.011	12.405	20.616

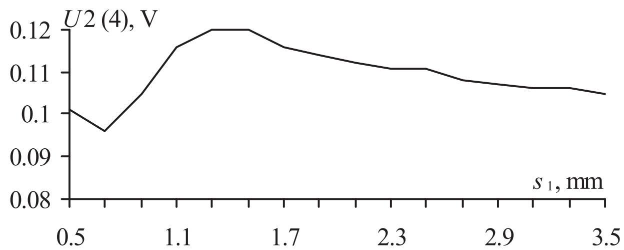


Fig. 5. Dependences of the amplitude of *U*2 (4) on s_1.

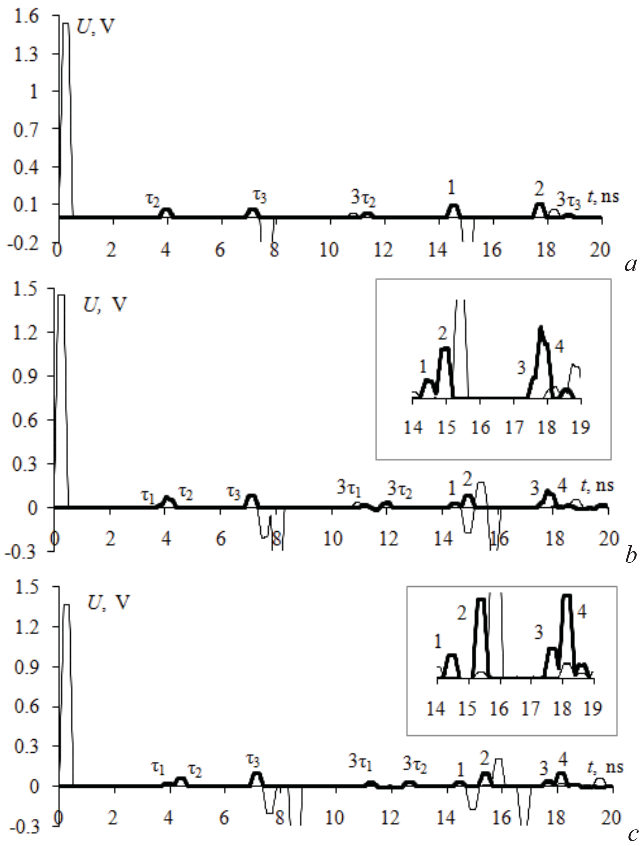


Fig. 6. Voltage waveforms at the MF input (-) and output (-) with «OC–SC» on the passive conductor for s_1=3.5 (*a*), 1.1 (*b*), 0.5 mm (*c*) and *l*=1 m.

For a more detailed study of additional pulses, the line length was increased to 2.5 m (Fig. 7). Since the moments of arrival of additional pulses between $3\tau_1$, $3\tau_2$ and $5\tau_1$, $5\tau_2$ are given in the previous section, only additional pulses that appear in the “OC-SC” case are considered here. Tables VI and VII show the resulting combination and the arrival time of additional pulses. From these data and Fig. 7, it can be concluded that the delays of additional pulses are determined by a linear combination of the per-unit-length delays of the line modes multiplied by the line length. It is also seen that with increasing asymmetry, the intervals between additional pulses become longer. So, for s_1=1.1 mm (Fig. 7*b*), the difference between 1 and 2 pulses is 1.175 ns and 0.5902 ns between pulses 3 and 4, then for s_1=0.5 mm (Fig. 7*c*) it is larger and makes 2,326 ns between 1 and 2 pulses and 1.173 ns between 3 and 4 pulses.

TABLE VI
ARRIVAL TIME FOR ADDITIONAL PULSES (NS)

№	1	2
View	$2\tau_2+\tau_3$	$\tau_2+2\tau_3$
s_1=3.5 мм	35.679	43.604

TABLE VII
ARRIVAL TIME FOR ADDITIONAL PULSES (NS)

№	3	4	5	6
View	$\tau_3+2\tau_1$	$2\tau_2+\tau_3$	$\tau_2+\tau_3+\tau_1$	$\tau_2+2\tau_3$
s_1=1.1 мм	35.533	36.708	43.5362	44.1264
s_1=0.5 мм	35.526	37.852	43.529	44.702

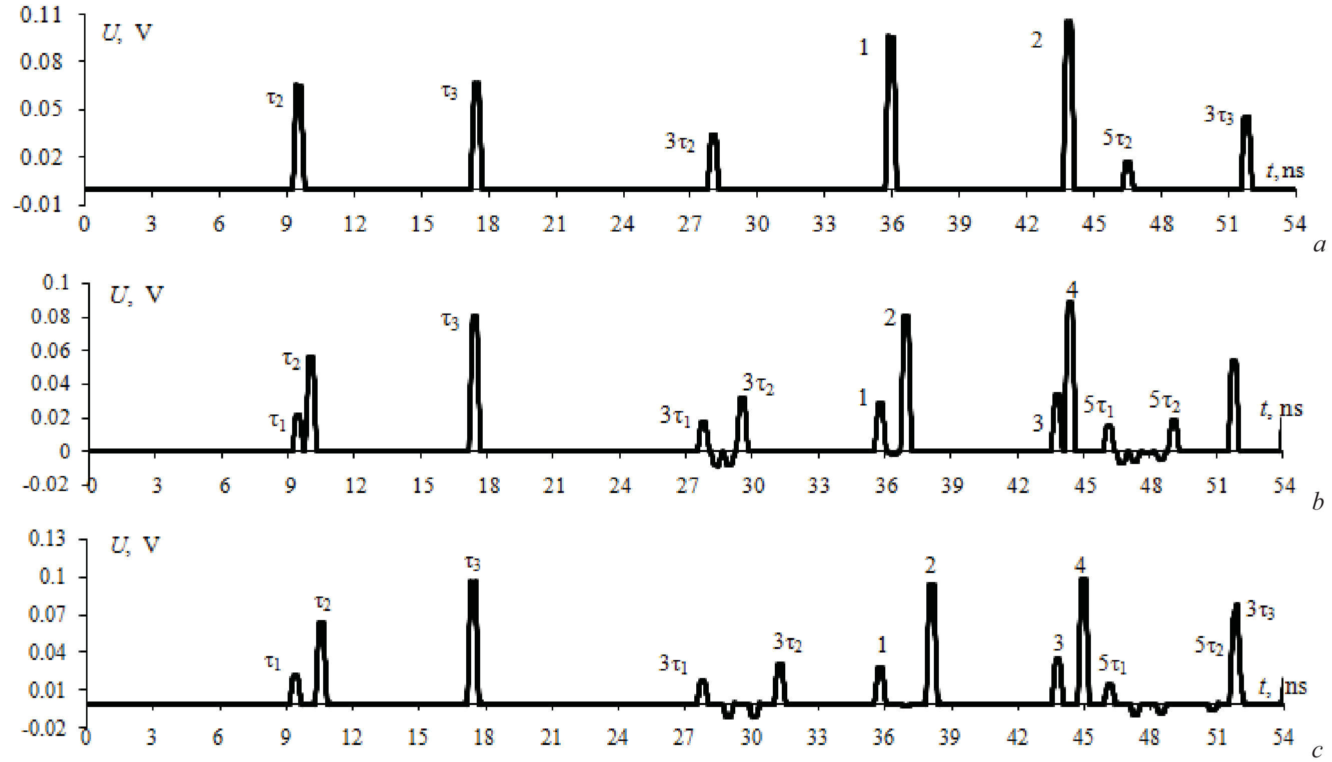


Fig. 7. Voltage waveforms at the MF output with «OC–SC» on the passive conductor for s_1=3.5 (*a*), 1.1 (*b*), 0.5 mm (*c*) and *l* =2.5 m.

V. CONCLUSION

Thus, the effect of asymmetry in the MF with a passive conductor in the cutout of the reference plane is shown. The asymmetry made it possible to decompose also the pulses of two fast modes (the difference in their per-unit-length delays was 0.46 ns/m), which allowed for the reduction of the maximum of the pulse amplitudes. But the increase of asymmetry results in the appearance of additional pulses, the delays of which are determined by a linear combination of the linear delays of the line modes multiplied by the line length.

It was shown that due to a change in the boundary conditions, a greater attenuation of the USP can be achieved, but additional pulses appear, the amplitude of which is greater than the amplitude of the pulses of the three modes. The increase in asymmetry allows decomposing pulses with larger amplitude into 4 pulses, thereby reducing their amplitude up to 10.4 times with respect to half the e.m.f.

The revealed fact makes further investigation of the effect of asymmetry in the MF relevant. This can make it possible to equalize the differences in the per-unit-length delays of the modes, as well as the amplitudes of their pulses. It is also important to conduct a detailed study of additional pulses that arise both with MF asymmetry and with symmetry in the passive conductor boundary conditions "OC-SC" and "SC-OC".

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