Simulation of the Time Response in Multiconductor Microstrip Modal Filters with Separate Accounting for Losses in Conductors and Dielectrics

Anton O. Belousov and Talgat R. Gazizov

***Abstract*— The protection of radio electronic equipment against ultrashort pulses (USPs) by means of modal filters (MFs) is considered. The structures of multiconductor microstrip MFs are analyzed. The time response simulation of 2–5 conductor MFs with length of 100 cm and 60 cm on excitation of USPs with duration of 1060 and 108 ps is performed. The separate effect of losses in conductors and dielectrics on the output signal is presented. The decrease of the output signal amplitude is shown in details. The effect of dispersion on signal waveform is illustrated. It was revealed that the effect of losses in conductors and dielectrics on individual modes can be mutually compensated to minimize output amplitude.**

***Index Terms*— protection devices, modal filters, microstrip lines, transmission line losses.**

I. Introduction

CONTEMPORARY radio-electronic equipment (REE) has a wide range of functional capabilities but, at the same time, they are susceptible to electromagnetic interference. Conducted interference is considered to be the most harmful one, as it can penetrate into devices directly through conductors [1]. Modern generators of ultrashort pulses have very high capabilities [2]. Such ultrashort pulses are able to penetrate and disturb the electronics due to the high power output and short duration. Therefore, it is necessary to improve the protection of electronics against ultrashort pulses. Meanwhile, attention to usage of distortions of a signal in the active line is not sufficient. So, the distortions are shown in a real example of three coupled microstrip lines [3]. Modal distortions meander delay lines are considered [4]. However, these distortions can bring benefits, in particular for protection.

A technique of modal filtration [5] was proposed for the protection of REE against ultrashort pulses. This technique is based on pulse signal modal decomposition which occurs due to a difference between the modal delays in multiconductor transmission lines. A number of studies [6–14] on the use of multiconductor microstrip lines (MSLs) as protective devices against ultrashort pulses have been performed. To inform an interested reader about these studies, a brief overview is provided in the next paragraph.

The results of simulation of MSL consisting of N=3, 4, 5 conductors showed the decomposition of an input pulse into 3–5 pulses at the end of a conductor with the maximum amplitudes of 3, 3.6 and 4.5 times (correspondingly) less than a signal at the near end of a line [6]. Optimization showed that the equalization of the differences between delays of decomposition pulses allows increasing duration of a pulse which is going to be completely decomposed in these structures [7]. In addition, the formulation of the main criteria for optimizing a multiconductor modal filter (MF) has been performed and an example of its optimization by criteria of the minimization of output amplitude and the maximization of a difference of time delays between the first and the last decomposition pulses has been given [8]. Experimental confirmation of the modal filtration based on multiconductor MSL was performed. For two- and three-conductor MSL, the attenuation of 11.5 and 13.7 times was obtained [9] respectively, and for four- and five-conductor – 12.6 and 15.3 times correspondingly [10]. In [6–10], a heuristic search for parameters was used, but it did not provide the best results. This disadvantage is eliminated in [11] based on MF optimization of the three-conductor MF by using a genetic algorithm (GA) providing the output MF amplitude 13% less than after the heuristic search. However, in [5–11] the only criterion was used for the optimization. In [12] a general objective function for the optimization with respect to several criteria was formulated and basic optimization criteria were detailed and for example four-criteria optimization of four parameters of a three-conductor microstrip MF was performed. Nevertheless, in [12] the matching of tract is neglected. In addition, multicriteria optimization of a four-conductor microstrip MF by a genetic algorithm has not been performed before. This disadvantage is eliminated in [13] wherein multicriteria optimization of a four-conductor microstrip MF with the matching criterion was performed. However, in [6–13] the time response on excitation of only dangerous ultrashort pulses was investigated, while the MF

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effect on propagation of useful high-frequency signals was not previously investigated. This gap was filled in paper [14] wherein the study of the frequency characteristics of multiconductor MFs was performed.

Meanwhile, during the preliminary modeling in [9–14], the losses in MSL were not considered properly. Therefore, it is useful to study carefully the effects of losses in multiconductor MFs. It is advisable to start it with a separate effect of losses in conductors and dielectrics on the voltage waveform at the the MF output. The aim of our research is to carry out such study. Obviously, it is difficult to perform experimentally, but it can be easily done by simulation.

II. Structures and Schemes of MFs under Consideration

For simulation, multiconductor MSL of length l=100 and 60 cm was chosen. MFs of 2–5 conductors are considered, which detailed research, as well as a full-scale experiment in the time domain, are performed in [9, 10]. The cross sections of these lines are shown in Fig. 1 where w – width of conductors, s_i – separations between them, t – thickness of conductors and h – thickness of dielectric substrate. Schematic diagrams of these MFs are shown in Fig. 2. The following parameters were chosen: w = 1000 µm, t = 18 µm and h = 500 µm, relative permittivity is ε_r = 3.8 and dielectric loss tangent tgδ = 0.017. The value of w was optimized in order to assure 50 Ω characteristic impedance of a single line and it was unchanged, as well as the values of t, h, ε_r and tgδ. Values of s_i are different for all lines, as they were optimized by criterion of minimization of the maximum voltage of a waveform at the output of a MSL [6]. In the case of two-conductor MF for length of l=100 cm s = 350 µm, for three-conductor – 200 and 800 µm, for four-conductor – 200, 800 and 50 µm, and for five-conductor – 200, 800, 500 and 800 µm correspondingly, and for a length 60 cm – 320 µm; 200 and 685 µm; 200, 720 and 550 µm and 200, 220, 200 and 800 µm for 2–5 conductors MSLs correspondingly.

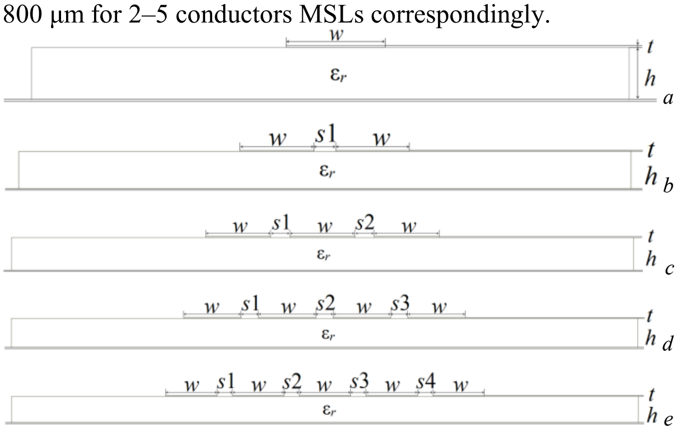


Fig. 1. Cross sections of one- (*a*), two- (*b*), three- (*c*), four- (*d*) and five-conductor (*e*) MFs

MF parameters and signal forms were calculated using TALGAT software [15]. It was assumed that a T-wave propagates along a MF. A digitized signal of the C9-11 oscilloscope was used as an exciting pulse; it was measured at 50 Ω load with an amplitude of 0.60901 V and an exciting pulse with an amplitude of 0.64398 V. For the length of the line 100 cm durations of rise – 518 ps, fall – 540 ps and flat top – 2 ps, so that the overall duration – 1060 ps, and for 60 cm durations of rise – 56 ps, fall – 48 ps and flat top – 4 ps, so that the overall duration – 108 ps. (Durations were measured at levels of 0.1–0.9). The forms of the initial pulses are shown in Fig. 3.

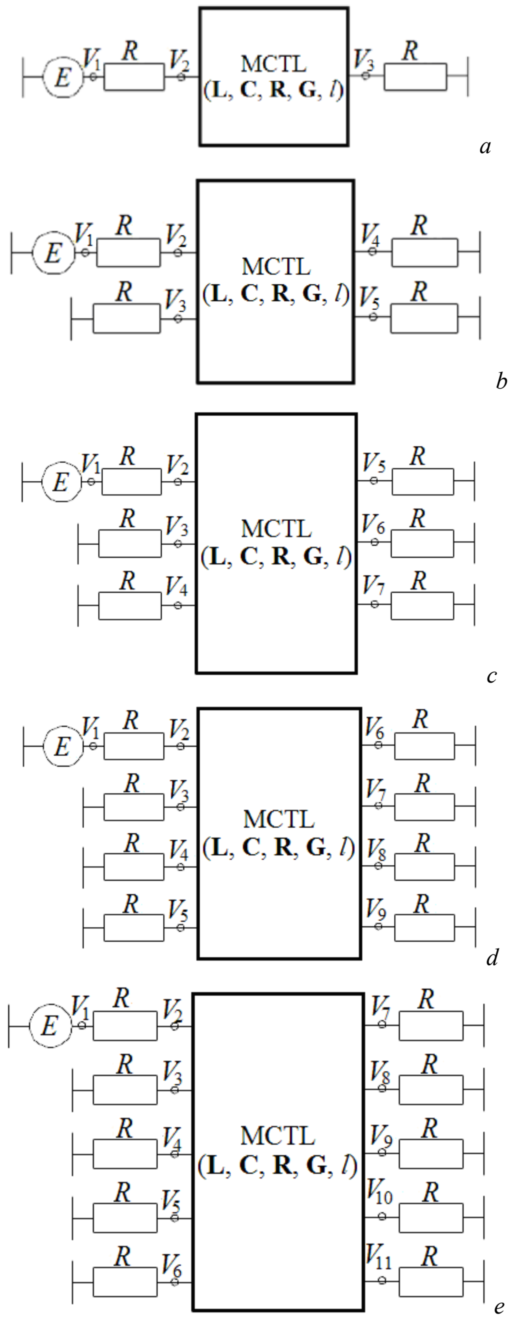


Fig. 2. Schematic diagrams of one- (*a*), two- (*b*), three- (*c*), four- (*d*) and five-conductor (*e*) MFs

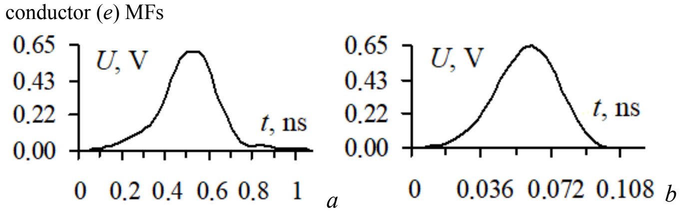


Fig. 3. Waveforms of EMF for the overall duration 1060 ps (*a*) and 108 ps (*b*)

III. Effect of Losses in Multiconductor MFs

For lossless simulations, the entries of the resistance per-unit-length **R** matrix, with taking into account the losses in the conductors, and the per-unit-length conductivity matrix **G** taking into account the losses in the dielectrics were accepted to be equal to zero. When taking into account the losses, a widely known model [16] of the frequency dependence of the relative permittivity and tangent of the dielectric loss angle of FR-4 material was used for calculating the of the matrix **G**. The entries of the matrix **R** were calculated taking into account the skin effect, the proximity effect and losses in the ground plane by the method proposed in [17].

When a signal with t_Σ=1060 ps is applied to a multiconductor MF with length of 60 cm, the signal does not decompose completely. On the other hand, when a pulse with t_Σ=108 ps is applied to the 100 cm line, the signal decomposition is guaranteed. Meanwhile, it seems interesting to decompose a pulse with t_Σ=1060 ps in a line with a length of 100 cm and t_Σ=108 ps in a line with a length of 60 cm. Thus, we simulate the 100 cm long line for t_Σ=1060 ps, and the 60 cm for 108 ps. The output waveforms of the N-conductor structures are calculated. The values of the pulse amplitudes at the output, with losses and lossless are summarized in Table I. The voltage waveforms at the output of multiconductor MFs with losses, lossless, and also with losses only in conductors and only in dielectrics are given in Table II.

TABLE I. Output amplitude (V) for N-conductor structures

N	Lossy		Lossless	
	1060 ps	108 ps	1060 ps	108 ps
1	0.1957	0.0647	0.306	0.3064
2	0.0882	0.0330	0.1550	0.1595
3	0.0761	0.0249	0.1377	0.1197
4	0.0755	0.0247	0.1439	0.1094
5	0.0755	0.0236	0.1433	0.0850

So, with losses, the amplitude of the signal at the output of a single-conductor MSL with length l=100 cm excited by pulse with t_Σ=1060 ps and EMF of 0.609 V is attenuated at the output to 0.196 V, which is 3.11 times less than the initial EMF level, whereas for the pulse with t_Σ=108 ps and EMF of 0.644 V the output attenuates to 0.065 V, which is 9.95 times less than the initial EMF level (with a line length of only 60 cm).

Analyzing Table II, we can note a significant effect of losses on the signal amplitude. Thus, in single-conductor MSL, the signal amplitude at the output for the case of t_Σ=1060 ps, l=100 cm for lossless simulation is 0.302 V. When losses are taken into account separately in conductors, dielectrics and both of them, the amplitude decreases to 0.218, 0.201 and 0.15 V, which is 1.4, 1.5 and 2 times less than in lossless simulation. We can see that losses in dielectrics have a considerable effect on the resulting amplitude level, which is more clearly observed for the case of t_Σ=108 ps, l=60 cm. Thus, when losses are taken into account separately in conductors, dielectrics and both of them, the amplitude of the signal at the MSL output is 0.192, 0.09 and 0.06 V, which are 1.68, 3.6 and 5.4 times less than the signal amplitude for lossless simulation (0.323 V).

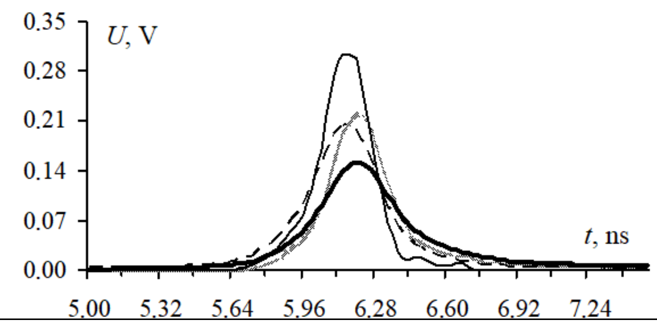
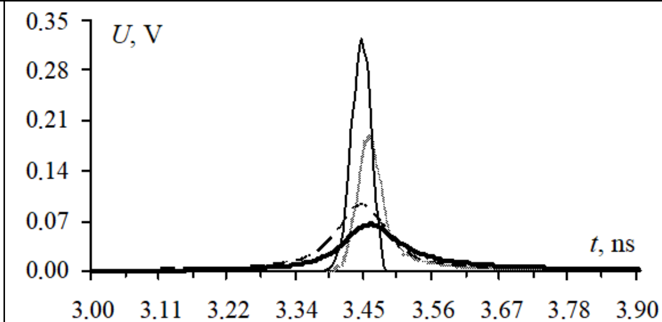
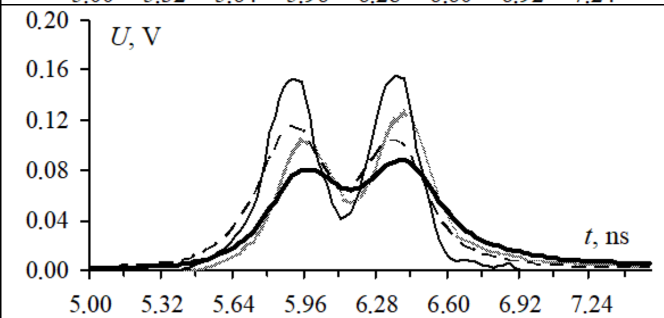
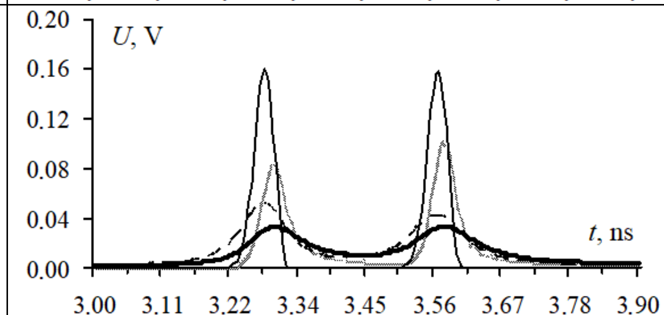
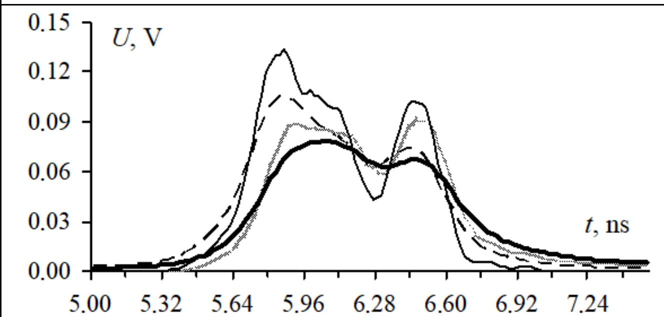
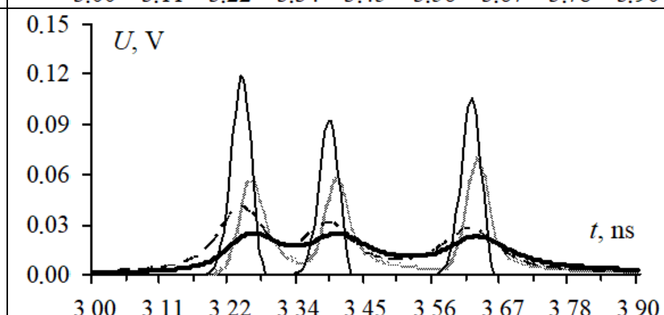
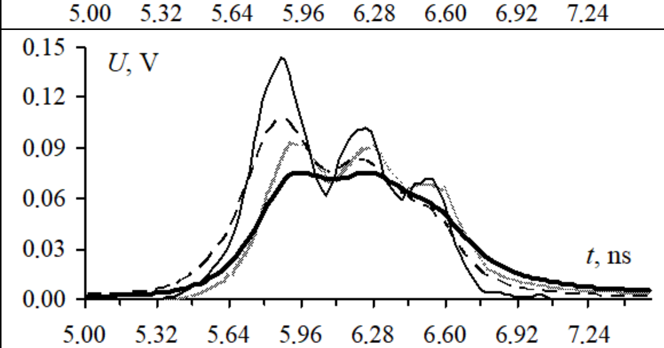
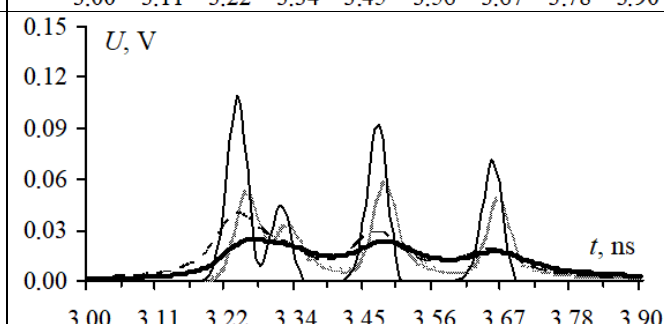
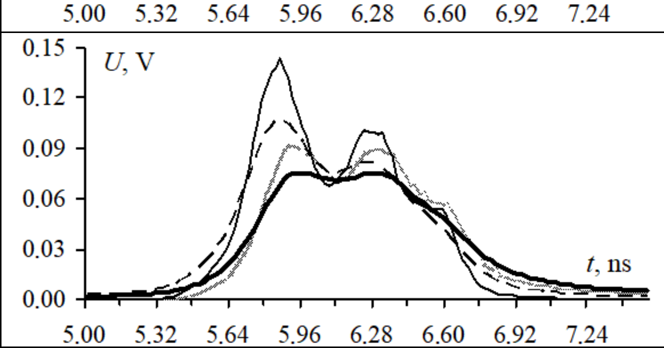
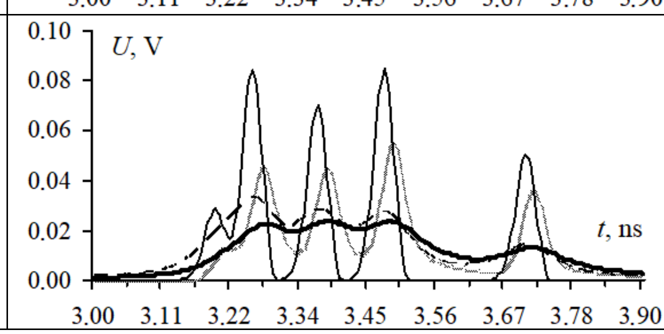
When losses in dielectrics are taken into account, non-causality is observed in the form of a premature arrival of a pulse signal, which is especially pronounced in case of t_Σ=108 ps, l=60 cm. Thus, for simulation with N=1, without taking into account the losses, as well as in simulation with losses in conductors, the signal comes to an output in time of 3.388 ns, whereas taking into account the losses in the dielectric alone and with losses in general, the arrival time of the pulse signal to the end of the line shifts to 3 ns. This is explained by an inaccurate accounting of the frequency dependence of ε_r in simulation taking into account the losses in the dielectric.

Meanwhile, the effect of losses in conductors leads to a signal waveform shift, relative to the signal waveform at the output, obtained in the lossless simulation. There is also a difference between the rise time of such a signal and the fall time. Thus, the rise time of the output signal for N=1 in case of t_Σ=108 ps, l=60 cm is 32 ps, and the fall time is 88 ps, i.e. they may vary by 2 to 3 times.

For N>1, there are different effects of losses in conductors and dielectrics on individual modes. To avoid superimposing impulses, and, as a consequence, a fuzzy picture, let us consider the effect of losses on individual modes in the case of t_Σ=108 ps, l=60 cm. Thus, when N=2, the amplitude of the signal at the output, taking into account the losses in the conductors for the odd mode, is equal to 0.081 V, and for the even one it is 0.1 V, while taking into account losses in the dielectric, the amplitude of the odd mode is 0.05 V and the amplitude of the even mode 0.04 V. Similarly, for N=3, when the losses in conductors are taken into account, the pulse amplitude of the first mode is 0.0557 V, of the second – 0.0562, of the third – 0.067 V, and when losses in dielectric are taken into account, 0.039, 0.029 and 0.026 V for the first, second and third modes, respectively. It is obvious that the impulse is superimposed with N increasing, in view of the insufficient line length, which makes it difficult to fully estimate the effect of losses in lines with a large number of conductors. However, the tendency of the amplitude level increasing of the output signal modes in the simulation taking into account losses in conductors, and its decrease when taking into account losses in dielectrics, with N increasing, nevertheless, has continued.

It is clear from the simulation with losses that such effect of losses in conductors and dielectrics on individual modes, in general, leads to minimization of the resulting amplitude level. Thus, when N=2 for t_Σ=108 ps, l=60 cm, the amplitude in modeling taking into account losses, is 0.32 V for the odd and even modes. For N=3, the amplitude is 0.024 V for the first and second modes and 0.023 V for the third mode.

TABLE II. WAVEFORMS AT THE OUTRUT OF *N*-CONDUCTOR STRUCTURES: LOSSLESS (——), WITH LOSSES IN CONDUCTORS (···), DIELECTRICS (- - -) AND WITH LOSSES (——)

<table>
<tr><th>N</th><th>t_Σ=1060 ps, l=100 cm</th><th>t_Σ=108 ps, l=60 cm</th></tr>
<tr><td>1</td><td></td><td></td></tr>
<tr><td>2</td><td></td><td></td></tr>
<tr><td>3</td><td></td><td></td></tr>
<tr><td>4</td><td></td><td></td></tr>
<tr><td>5</td><td></td><td></td></tr>
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IV. CONCLUSION

Thus, the paper is the first to present the results of the research of losses effects in conductors and dielectrics separately, on the example of multiconductor MFs. As seen in Table I, the initial duration of exciting pulse strongly affects the attenuation of the signal, even in the case of a single-conductor MSL.

Losses in conductors and dielectrics affect signal waveform at the line output in different ways, as shown in Table II. It is seen that the effect of losses leads to decrease of decomposition pulses amplitude and to increase their duration due to dispersion.

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