Simulation of Ultrawide Band Pulse Propagation in Asymmetrical Modal Filter for Power Network Protection

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Abstract**—** Use of modal filtration is proposed as a new approach of power network protection against threat of ultrawide band pulses. A new structure of modal filter, based on widely used FR-4 material, is considered. Dependencies of its characteristics on width and separation of conductors and thickness of a dielectric are simulated. Possibility for modal filter 0.75 m in length to decrease by factor 7 the magnitude of an input pulse with total duration of 3 ns is shown. Possibility of fast estimations for asymmetrical structures of modal filter is revealed. Results of complete simulation of asymmetrical modal filter structure extended to simulation taking into account frequency depended losses both in conductors and dielectrics are presented and compared with lossless case. Considerable attenuation of odd mode pulse resulting in some decrease of total signal magnitude at modal filter output is revealed.

Keywords—modal filter, protection, ultrawide band pulse, frequency depended losses, coupled lines.

I. INTRODUCTION

NOWADAYS there is an increasing threat of the impact of ultrawide band (UWB) pulses in power systems. Such an impact can result in a malfunction or failure of electronic equipment. Therefore, protection of computer devices and systems, controlling the critical equipment (especially energy equipment), is extremely important [1]. The most common devices for electronics protection against undesired electrical pulses are varistors and gas discharge tubes, and their combinations can considerably improve the protection performance [2]. However, existing surge protectors do not protect against UWB pulses [3]. It is known only about some industrial devices that protect against UWB pulses but have large dimensions and high cost. Thus, currently there is no both effective and cheap protection against UWB pulses. However, the increasing role of electronics in our life makes this protection essential.

The idea of modal filtration has been suggested recently and several devices based on modal filtration principle have been developed. Among them there are symmetrical structures of modal filters (MF) for the Fast Ethernet network [4], for lightning [5] and electrostatic discharge [6] protection. However, the usage of the MF in power systems is investigated insufficiently. The MF based on PCB technology (PCB MF) built into the power supply filter has been considered recently, and it has been shown, that such an application of the MF can provide effective and cheap protective device [7].

In the above paper we have proposed creation of the MF embedded to a power supply filter for UWB pulses suppression. For example, the MF can be formed as a thin strip of foiled fiberglass and this strip can be inserted into a socket unit: a separate one or as a part of a power supply filter. To realize this idea preliminary analysis of the possibility of MF usage in the power network and tentative simulation of electrical characteristics of a device have been done. However, the simulation has been performed without taking into account losses in conductors and dielectrics. Meantime, such an accounting can be important to obtain more realistic results for proper MF design.

The aim of this paper is to present results of complete simulation of asymmetrical MF structure extended to simulation taking into account frequency depended losses both in conductors and dielectrics and compared with lossless case. For completeness of presentation brief comparison of various approaches is shown, and lossless simulation results obtained in [7] are presented. Then, new results of more realistic simulation are presented and compared.

II. COMPARISON OF PROTECTORS

Creation and implementation of the MF prototype embedded in the process of power supply filters production opens several prospective advantages over existing solutions. Initial comparison of characteristics of the proposed MF and existing devices (a typical surge protector and special industrial design of a new UWB pulse suppression filter [8]) is presented in Table 1. It can be seen that the MF built in the power supply filter combines all the advantages of common devices, and at the same time it costs just slightly more expensive.

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Table 1. Comparison of characteristics of the protective devices [7]

Parameters	Modal filter	Surge protector	Industrial Filter
Duration of impulse noise (ns)	<1	>1	<1
Cost (rub.)	50+cost of surge protector	500–2500	183000
Dimensions	Inside the surge protector	Surge protector dimensions	400*300*5 mm
Resistance to radiation	High	Low	High
Durability	High	Low	Low

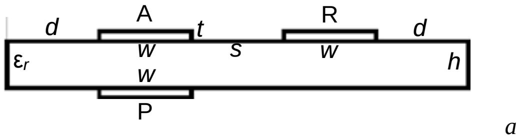
Thus, the proposed solution can provide an affordable, popular and effective protection of electronic devices from UWB pulses propagating through the mains.

III. Lossless Simulation

Simulation of electrical characteristics is often carried out with use of electromagnetic analysis, especially, in a case of 3D-structure scattering problem [9]. However, for long 2D-structures a quasi-static approach is often relevant. Particularly, it allows to obtain causal results taking into account frequency dependent losses in conductors and dielectrics [10]. In this paper we use quasi-static analysis based on fast and accurate models [11], implemented in available TALGAT system. In the analysis it is assumed that a transmission line is uniform along its length with an arbitrary cross section. The cross section, with N signal conductors and a reference, is represented by the following $N\times N$ matrices of line per unit length parameters: inductance (**L**), coefficients of electrostatic induction (**C**), resistance (**R**), conductance (**G**). In paper [12] an approach based on a modified nodal admittance matrix has been presented for formulation of network equations including the coupled transmission line, terminal, and interconnecting networks. Voltages in the time domain are obtained by applying the inverse fast Fourier transform.

Matrixes **L** and **C** are calculated by a method of moments with following parameters of the proposed MF having asymmetrical cross section (Fig. 1*a*): separation of conductors s=5, 10, 15 mm; width of conductor w=5, 10, 15 mm; dielectric thickness h=0.5; 1; 1.5 mm (typical substrate values); conductor thickness t=105 µm (high thickness of foil to withstand high currents); distance between the edge of the structure and the conductor d=w; relative permittivity ε_r=4 (cheap and widely used FR-4).

Firstly, calculation of time response is carried out in a lossless approximation. Pulse signal was excited between active (A) and reference (R) conductors (Fig. 1*a*). The MF circuit diagram is shown in Fig. 1*b*, where e.m.f. source parameters: rise, top and fall times t_r=t_f=t_d=1 ns while the magnitude is 2 V; length l=0.75 m; U1–U5 – nodes; R – resistances equal to geometric mean of even and odd modes impedances.



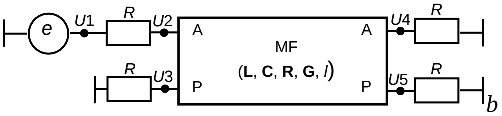


Fig. 1. Cross section (*a*) and circuit diagram (*b*) of the MF

Waveforms at the near and far ends of an active conductor of the MF and also a number of important parameters are calculated. Among them there are per unit length delays of even and odd modes and their differences, geometric means of even and odd modes impedances, MF attenuation coefficient calculated by analytic formula (obtained for the MF cross sections being symmetrical about a reference conductor) [13]:

$$U_A=2k/(k+1)^2, \qquad (1)$$

where $k=(Z_e/Z_o)^{1/2}$ with $Z_e>Z_o$.

Waveforms, calculated for h=0.5; 1; 1.5 mm without losses, are shown in Fig. 2–4 respectively, and other parameters are presented in Table II. It should be noted that the waveforms are presented only for s=5 mm, because effects of the s value on calculated waveforms for each w value are negligible. Meantime, the small effects exist, and to show it the calculated parameters for each s value are presented in Table II.

As one can see from the plots of Fig. 2–4 there is no complete pulse decomposition with selected parameters of the structure and the pulse. However, the complete pulse decomposition is not required, because it only increases an undershoot between two decomposed pulses not decreasing their magnitudes (see Fig. 2). On the other hand, the increase of two pulses overlapping increases an overshoot degrading the protection (see Fig. 4). In any case, the desired result can be achieved by proper choice of the MF parameters with defined pulse duration. For example, it is enough to achieve the MF output waveform (U_4) as in Fig. 2*a* or Fig. 3*c*. Anyway, one can see from Fig. 2–4 that the MF attenuates input pulse, because U_4 value is less than U_2 value about: 5.3 times for h=0,5 mm; 4 times for h=1 mm; 3.5 times for h=1,5 mm. As for w value, its increasing improves attenuation for defined h values.

From the Table II it can be seen that the maximal value of the per unit length modal delays difference is about 3 ns/m for h=0.5 mm and the value decreases to 2.67 ns/m with increase of the h value (Table II, w=s=15 mm). It increases slightly with increase of the s value for defined w value, while it increases more considerably with increase of the w value for the defined s value. Exact estimations can be seen from Table II.

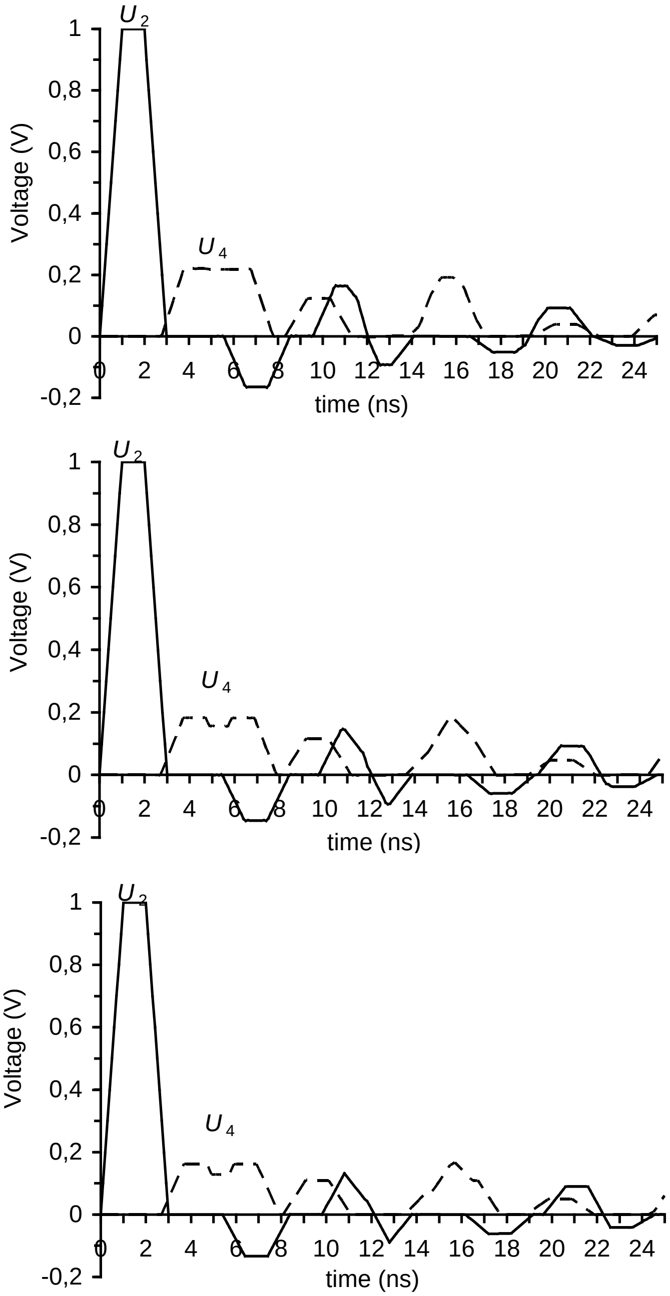


Fig. 2. Waveforms at the near and far ends of an active conductor of the MF with *h*=0.5 mm, *s*=5 mm for *w*=5 (*a*), 10 (*b*), 15 (*c*) mm [7]

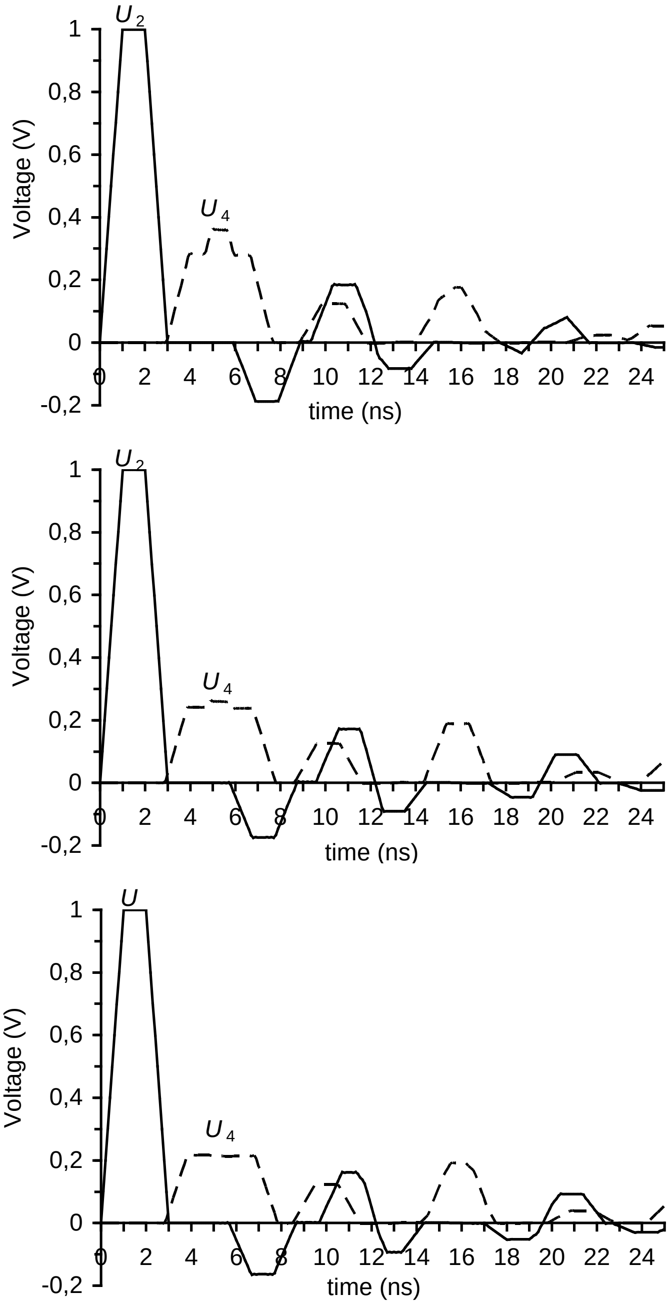


Fig. 3. Waveforms at the near and far ends of an active conductor of the MF with *h*=1 mm, *s*=5 mm for *w*=5 (*a*), 10 (*b*), 15 (*c*) mm [7]

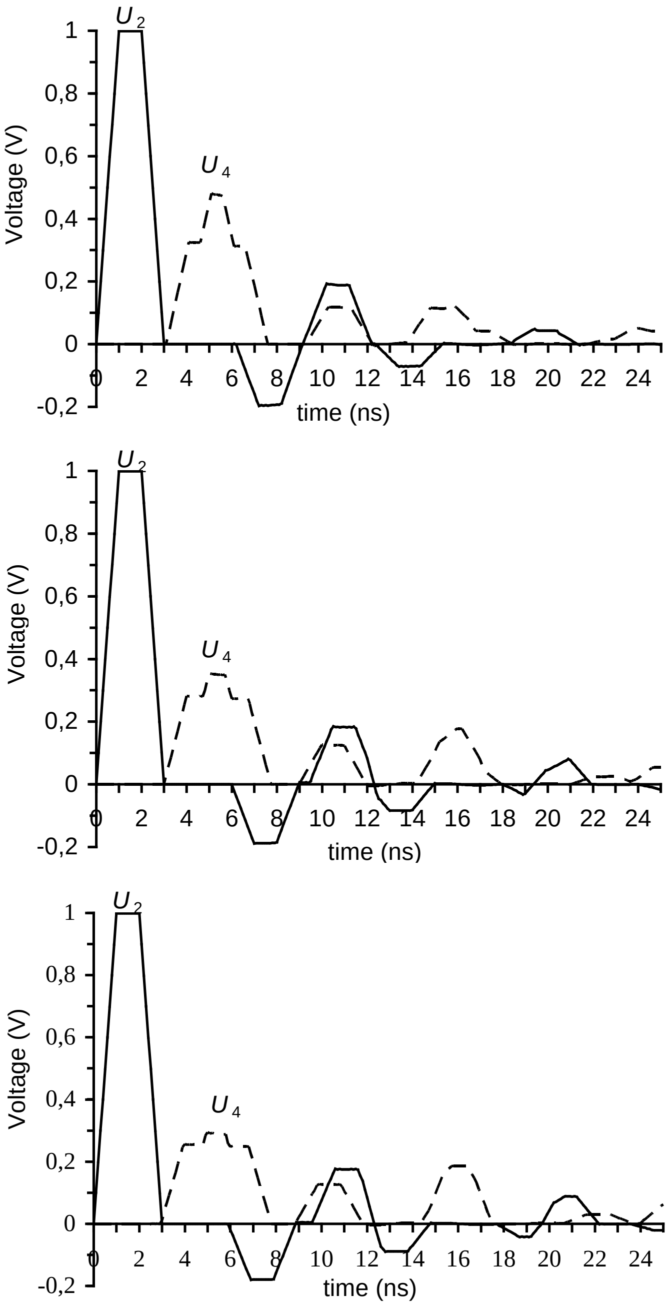


Fig. 4. Waveforms at the near and far ends of an active conductor of the MF with h=1.5 mm, s=5 mm for w=5 (*a*), 10 (*b*), 15 (*c*) mm [7]

It is important to note that similar dependences on *h*, *s* and *w* are also observed for magnitudes of decomposed pulses as it may be concluded after close examination of two last columns of the Table II. However, there is another important conclusion also. Comparison of decomposed pulses magnitudes obtained from analytic calculations using (1) (U_A) and from waveforms (U_S) show its very close coincidence. Consequently, the analytic formula (1) obtained for symmetrical MF structures can be used for fast estimations of asymmetrical MF structures, at least, in the considered (matched) case when all the resistances are equal to geometric mean of the even and odd modes impedances.

Table 2. Per unit length delays of even and odd modes and their differences, geometric means of even and odd modes impedances, magnitudes of decomposed pulses (analytics and simulation) from Fig. 2–4

Fig.	w, mm	s, mm	τ_e, ns/m	τ_o, ns/m	$\Delta\tau$, ns/m	$(Z_eZ_o)^{1/2}$, Ω	U_A, V	U_S, V
2	5	5	3.69872	6.37276	2.67403	57.9027	0.219	0.22
		10	3.61557	6.37277	2.75721	65.2746	0.2	0.2
		15	3.57982	6.37278	2.79295	69.748	0.19	0.19
	10	5	3.62877	6.49007	2.8613	38.8676	0.182	0.184
		10	3.55632	6.49009	2.93377	43.5997	0.166	0.174
		15	3.52627	6.49009	2.96382	46.5709	0.157	0.167
	15	5	3.59534	6.53826	2.94292	30.629	0.161	0.162
		10	3.52749	6.53828	3.01079	34.1987	0.147	0.156
		15	3.49987	6.53828	3.0384	36.4754	0.139	0.15
3	5	5	3.93615	6.2275	2.29135	75.0687	0.28	0.28
		10	3.79757	6.22754	2.42997	85.3977	0.257	0.27
		15	3.73422	6.22755	2.49332	91.6787	0.244	0.26
	10	5	3.83132	6.38645	2.55513	51.5882	0.239	0.24
		10	3.70961	6.3865	2.67689	58.3563	0.218	0.23
		15	3.65593	6.38651	2.73058	62.5919	0.2	0.22
	15	5	3.77899	6.45671	2.67772	41.0766	0.215	0.21
		10	3.66448	6.45676	2.79228	46.2361	0.196	0.2
		15	3.61502	6.45677	2.84175	49.5065	0.186	0.2
4	5	5	4.12025	6.1263	2.00605	85.794	0.318	0.32
		10	3.94481	6.12636	2.18155	98.1383	0.293	0.311
		15	3.85987	6.12637	2.2665	105.719	0.279	0.3
	10	5	3.99303	6.30743	2.3144	60.0036	0.277	0.28
		10	3.83783	6.30754	2.46971	68.2368	0.253	0.269
		15	3.76535	6.30755	2.5422	73.4182	0.24	0.26
	15	5	3.92751	6.39198	2.46448	48.1629	0.251	0.25
		10	3.78086	6.39209	2.61123	54.4967	0.23	0.243
		15	3.7139	6.3921	2.6782	58.525	0.218	0.235

IV. SIMULATION WITH LOSSES

For the more accurate evaluation of the decomposed pulses magnitudes, simulation with losses in dielectrics and conductors is carried out. The losses are completely defined by the per unit length conductivity (**G**) and resistance (**R**) matrixes respectively. Frequency dependence of these matrixes is considered. Besides, frequency dependence of the complex FR-4 permittivity is taken into account by using of analytical model from [10]. The matrix **R** entries are calculated accounting a skin effect but without consideration of a proximity effect. All conductors have the same cross section, therefore diagonal (r) and non-diagonal (r_m) entries of matrix **R** are related by the expression

$$r=2r_m,$$

where $r_m=1/(w\sigma t)+r_s/w$, where σ – copper conductivity, $r_s=(\pi f\mu_0/\sigma)^{1/2}$, where f – frequency, μ_0 – free space permeability.

Comparison of waveforms at the far end of an active conductor, calculated for h=0.5; 1; 1.5 mm without and with losses, is shown in Fig. 5–7 respectively. It is seen that losses reduce pulses magnitude. The decrease is insignificant for even mode and rather considerable for odd mode. Unfortunately, it is difficult to reveal main reason of this difference because in the current simulation effects of several factors are combined. First of all, it is separate influence of losses in conductors and dielectrics. Moreover, impedance and per unit length delay undergo some changes. It is worth noting that these changes are different for even and odd modes. Identification of separate influence of each factor by experimental investigation is very difficult and costly. However, it is rather easy to carry it out with use of simulation, and it is assumed to do in further researches.

Nevertheless, performed simulation represents an integral influence of the losses on the waveform on the MF output. According to the waveforms, it is possible to determine an influence of the losses on the resulting MF attenuation. The maximal values of the output voltage for the cases without (*U*) and with (U_L) losses and their ratios are presented in Tab. 5. One can see that for both cases (without and with losses) the MF attenuation is improved by decrease of *h* value and increase of *w* value. For these trends the influence of losses is decreasing, but it becomes more pronounced (up to 66% relatively to lossless case) when increasing of *h* value and decreasing of *w* value. (This conclusion is important for choice of fast lossless simulation instead of time consuming simulation with losses.) It should be noted, however, that the main cause of such influence is explained by the revealed fact, that even mode undergoes small influence of losses, but it is the mode that defines the maximal value of output signal.

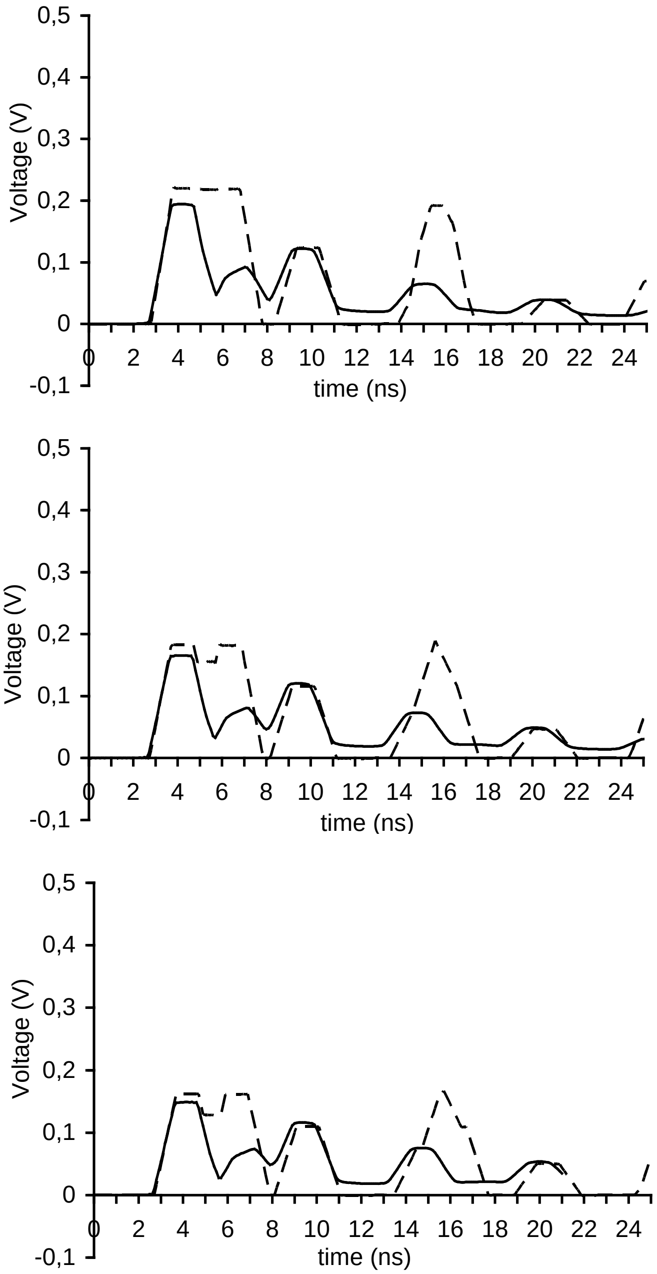


Fig. 5. Waveforms at the far end of an active conductor of the MF with *h*=0.5 mm, *s*=5 mm for *w*=5 (*a*), 10 (*b*), 15 (*c*) mm without (– – –) and with (——) losses

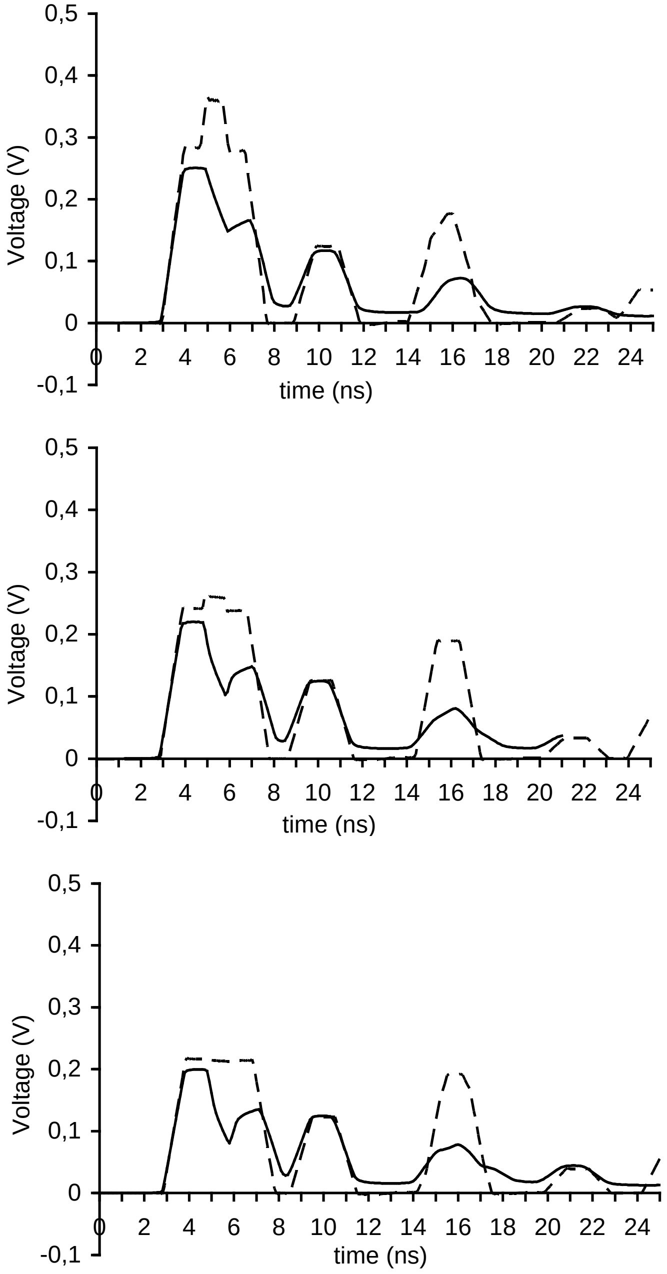


Fig. 6. Waveforms at the far end of an active conductor of the MF with h=1 mm, s=5 mm for w=5 (*a*), 10 (*b*), 15 (*c*) mm without (– – –) and with (——) losses

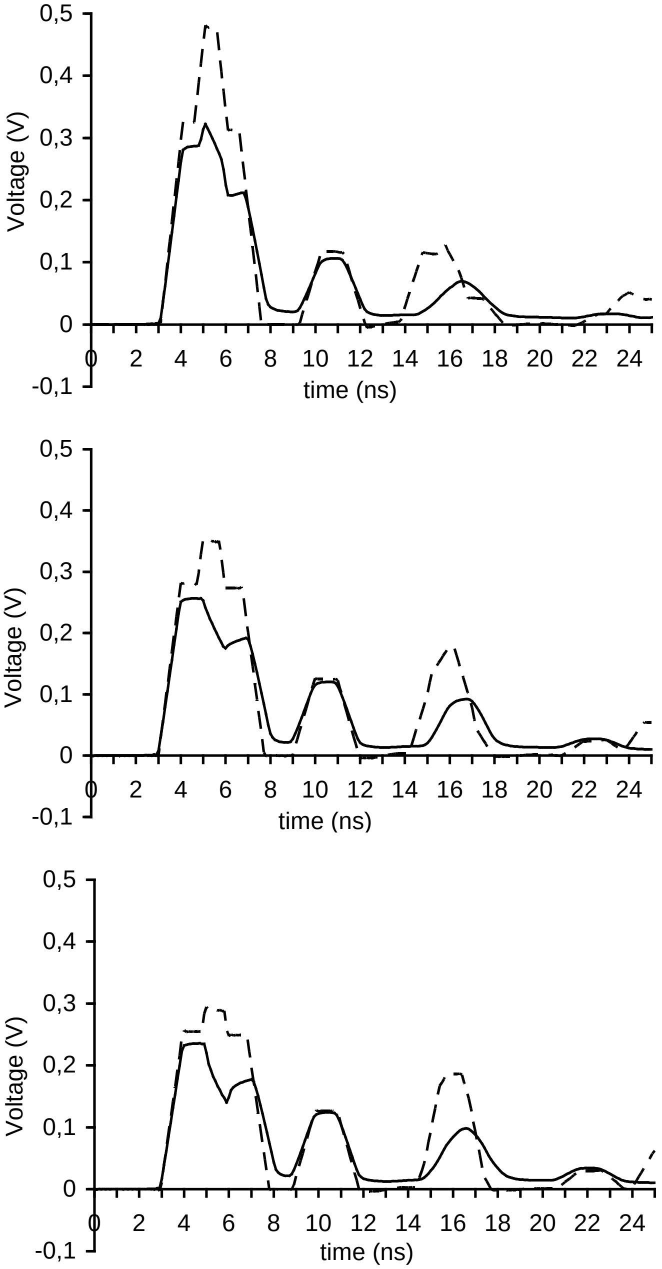


Fig. 7. Waveforms at the far end of an active conductor of the MF with h=1.5 mm, s=5 mm for w=5 (*a*), 10 (*b*), 15 (*c*) mm without (– – –) and with (——) losses

Table 3. Maximal values of the MF output voltage for the cases without (U) and with (U_L) losses and their ratios for s=5 mm

w, mm	h=0.5 mm			h=1 mm			h=1.5 mm		
	U, V	U_L, V	U_L/U	U, V	U_L, V	U_L/U	U, V	U_L, V	U_L/U
5	0.218	0.194	0.88	0.357	0.250	0.70	0.477	0.315	0.66
10	0.181	0.165	0.91	0.258	0.219	0.84	0.347	0.256	0.74
15	0.162	0.148	0.91	0.214	0.199	0.93	0.289	0.235	0.81

V. CONCLUSION

In this paper the asymmetrical structure examination has been carried out for the purpose of implementation of the MF, based on widely used FR-4 material for typical thicknesses of

0.5–1 mm with 105 µm foil thickness. Besides, calculations in parameter ranges which allow the evaluation of structure parameters influence on the difference between per unit length delays of modes and the evaluation of MF attenuation coefficient are accomplished. As a result, the maximal value of difference between per unit length delays of modes, 3 ns/m, and the maximal MF attenuation coefficient, 0.15, are obtained when h=0.5 mm, s=w=15 mm. It allows to decrease by factor 7 the magnitude of input pulse with total duration of 3 ns by MF 0.75 m in length. Moreover, the important possibility of fast estimations for the asymmetrical MF structures is revealed. At last, more accurate simulation taking into account frequency dependent losses in conductors and dielectrics shows considerable attenuation of odd mode pulse resulting in some decrease of total signal magnitude at modal filter output.

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