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Simulation the time response to ultra-short pulse excitation of two cascaded modal filters with a passive conductor in the reference plane

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Abstract. The paper considers protection of radio electronic equipment against conductive excitation of an ultra-short pulse (USP) by using a serial connection of two modal filters (MF) of the same length, which have a passive conductor in the cutout of the reference plane. The amplitude at the output was reduced by 12.5 times in relation to the half of the e.m.f. with 50 Ω resistors at the ends of the passive conductors. The influence of boundary conditions at the ends of the passive conductors of two MFs was considered. For OC-SC, OC-SC the amplitude reduction by 70 times was achieved.

1. Introduction

Ensuring electromagnetic compatibility (EMC) of different radio electronic equipment (EE) is becoming more and more important every year, as the number, variety and complexity of EE is rapidly growing. This leads to an increasing variety of electromagnetic interference. The most dangerous are conductive interferences, especially ultra-short pulses (USP) [1]. Examples of how USPs diversely effect the equipment are: failures in the control and management systems in production, failures in aircraft on-board systems, failures in medical diagnostic and life support equipment, communication line failures, information loss in the computer. Up-to-date protection devices have large dimensions and high cost, as well as low radiation resistance due to semiconductor elements [2-5]. Therefore, the search for new protection devices is relevant.

A new, simple and cheap in implementation means of protection against USPs is a modal filter (MF) [6]. One of the simplest options of MFs is obtained by modifying the microstrip line (MSL). The design of such an MF is formed by means of two cutouts in the ordinary MSL ground plane, which form a passive conductor between themselves. With the help of such MF the USP amplitude reduction achieves 4.54 times in case of weak coupling between active and passive conductors [7] and 5 times in case of strong coupling [8]. Based on the results obtained, two models of the MF with different connections were produced and a full-scale experiment was carried out. Since different communication between the conductors provides not only different attenuation, but also different modal delays (which will avoid impulse superimposition at the output of the second MF), more attenuation can be achieved by having two MFs connected in series. However, this option has not been considered before.

The purpose of this work is to carry out such a study.



2. Structure under investigation

Figure 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. Figure 1(b) shows the connection diagram on of two MFs with length l with matrices of per-unit-length parameters **L1**, **C1** and **L2**, **C2**. The substrate material chosen is foil-clad fiberglass ($\epsilon_r=4.5$), due to its cheapness, availability and wide application. The resistances $R1=R2=R4=R6=R8=R9=50 \Omega$, and for the connection of the edge conductors $R3=R5=R7=R10=1 \text{ m}\Omega$. The input excitation is a trapezoidal pulse with the following parameters: the e.m.f. amplitude is 2 V, the rise time is 50 ps, the flat top time is 50 ps, the fall time is 50 ps. The calculation of matrices, parameters and voltage waveforms is performed using the quasistatic approach in the TALGAT system [9]. Losses in conductors and dielectrics, in this first study, were not taken into account.

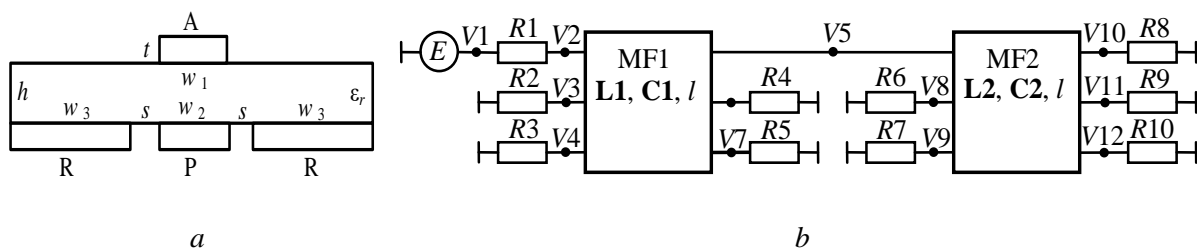


Figure 1. MF connection diagram (a) where the conductors: R – reference, A – active, P – passive. Cascaded MF circuit model (b).

3. Simulation results

Simulation was performed according to the parameters of the manufactured MF layouts, namely $t=35 \mu\text{m}$, $h=0.18 \text{ mm}$, $l=30 \text{ cm}$ at $w_1=w_2=w_3=1 \text{ mm}$ and $s=0.5 \text{ mm}$ (for MF1 with weak coupling) and $w_1=w_2=3.5 \text{ mm}$, $w_3=0.5 \text{ mm}$ and $s=3.0 \text{ mm}$ (for MF2 with strong coupling). Calculated matrices of per-unit-length parameters are the following:

$$\mathbf{C1} = \begin{bmatrix} 263.58 & -238.7 & -12.451 \\ -238.7 & 264.23 & -12.692 \\ -12.451 & -12.692 & 30.66 \end{bmatrix}, \text{ pF/m; } \mathbf{L1} = \begin{bmatrix} 615.13 & 525.15 & 432.46 \\ 525.15 & 608.05 & 432.36 \\ 432.46 & 432.36 & 864.73 \end{bmatrix}, \text{ nH/m; } \\
 \mathbf{C2} = \begin{bmatrix} 813.69 & -802.08 & -5.7986 \\ -802.08 & 813.74 & -5.8217 \\ -5.7986 & -5.8217 & 14.059 \end{bmatrix}, \text{ pF/m; } \mathbf{L2} = \begin{bmatrix} 1018.7 & 989.28 & 818.72 \\ 989.28 & 1018.33 & 818.72 \\ 818.72 & 818.72 & 1637.75 \end{bmatrix}, \text{ nH/m. }$$

Figure 2 shows the results of simulating the response. At node V5 (after MF1) two pulses are observed, which is explained by the fact that two fast modes come approximately at the same time, forming one pulse with amplitude addition at the output, and a slow one comes later. From this we can conclude that the output of MF2 (node V10) will receive 4 pulses. Table 1 shows the per-unit-length delays of the modes for MF1 (τ_{1i}) and MF2 (τ_{2i}), which will make it possible to calculate the pulse arrival time at the output of MF2.

Table 1. Per-unit-length mode delays for MF1 (τ_{1i}) and MF2 (τ_{2i}), ns/m

MF1			MF2		
τ_{11}	τ_{12}	τ_{13}	τ_{21}	τ_{22}	τ_{23}
3.95	4.20	5.59	3.67	3.72	6.87

The pulse arrival time at the output of MF2 (node V10) was calculated using the following formulae:

$$\begin{aligned}
 t_1 &= \tau_{11}l + \tau_{21}l = 2.28 \text{ ns}, & t_2 &= \tau_{11}l + \tau_{22}l = 2.30 \text{ ns}, & t_3 &= \tau_{11}l + \tau_{23}l = 3.24 \text{ ns}, \\
 t_4 &= \tau_{12}l + \tau_{21}l = 2.36 \text{ ns}, & t_5 &= \tau_{12}l + \tau_{22}l = 2.37 \text{ ns}, & t_6 &= \tau_{12}l + \tau_{23}l = 3.32 \text{ ns}, \\
 t_7 &= \tau_{13}l + \tau_{21}l = 3.08 \text{ ns}, & t_8 &= \tau_{13}l + \tau_{22}l = 3.09 \text{ ns}, & t_9 &= \tau_{13}l + \tau_{23}l = 4.04 \text{ ns}.
 \end{aligned}$$

As a result, 4 pulses with the pairs of the same amplitudes (U_1 (for t_5)=0.08 V, U_2 (for t_8)=0.08 V, U_3 (for t_6)=0.05 V and U_4 (for t_9)=0.05 V) were observed in the node V10. However, the pulses with delays t_8 and t_6 did not add up due to the short duration of the input excitation.

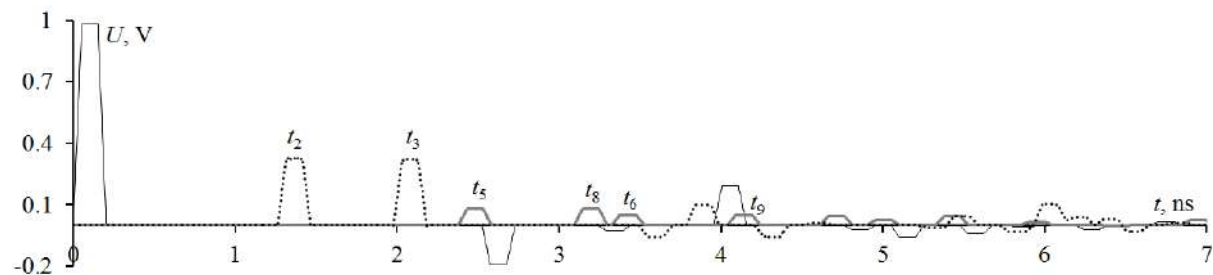


Figure 2. Voltage waveforms at the MF1 input (—), at the MF1 output (··) and MF2 output (-)

Consider the passive conductor connection without resistivity, which allows to increase the lifetime of the device and reduce its cost. By connecting two MFs in series, more options can be considered and even higher USP attenuation. The influence of the boundary conditions at the ends of the passive conductor was simulated as follows: “short circuit (SC) – open circuit (OC)” and their possible combinations. The combinations and amplitudes of decomposition pulses at the output of MF2 are shown in Table 2. The SC was simulated as $10^{-3} \Omega$, and the OC – $10^9 \Omega$. The results of simulating the voltage waveforms at the MF1 input and at the MF2 output are shown in Figure 3. The amplitudes of decomposition impulses for OC-SC, OC-SC are equal to $U_1=0.012$ V, $U_2=0.014$ V, $U_3=0.013$ V, $U_4=0.014$ V (Figure 3h), so the maximum reduction relative to half of the exiting e.m.f. was 70 times.

Table 2. Pulse amplitudes at MF2 output

Boundary conditions	$U_1, \text{ V}$	$U_2, \text{ V}$	$U_3, \text{ V}$	$U_4, \text{ V}$
50-50, SC-OC	0.024	0.024	0.025	0.025
50-50, OC-SC	0.023	0.023	0.024	0.024
SC-OC, 50-50	0.052	0.059	0.032	0.037
SC-OC, 50-50	0.053	0.060	0.033	0.038
SC-OC, SC-OC	0.013	0.012	0.014	0.014
SC-OC, OC-SC	0.017	0.020	0.018	0.020
OC-SC, SC-OC	0.020	0.020	0.022	0.023
OC-SC, OC-SC	0.012	0.014	0.013	0.014

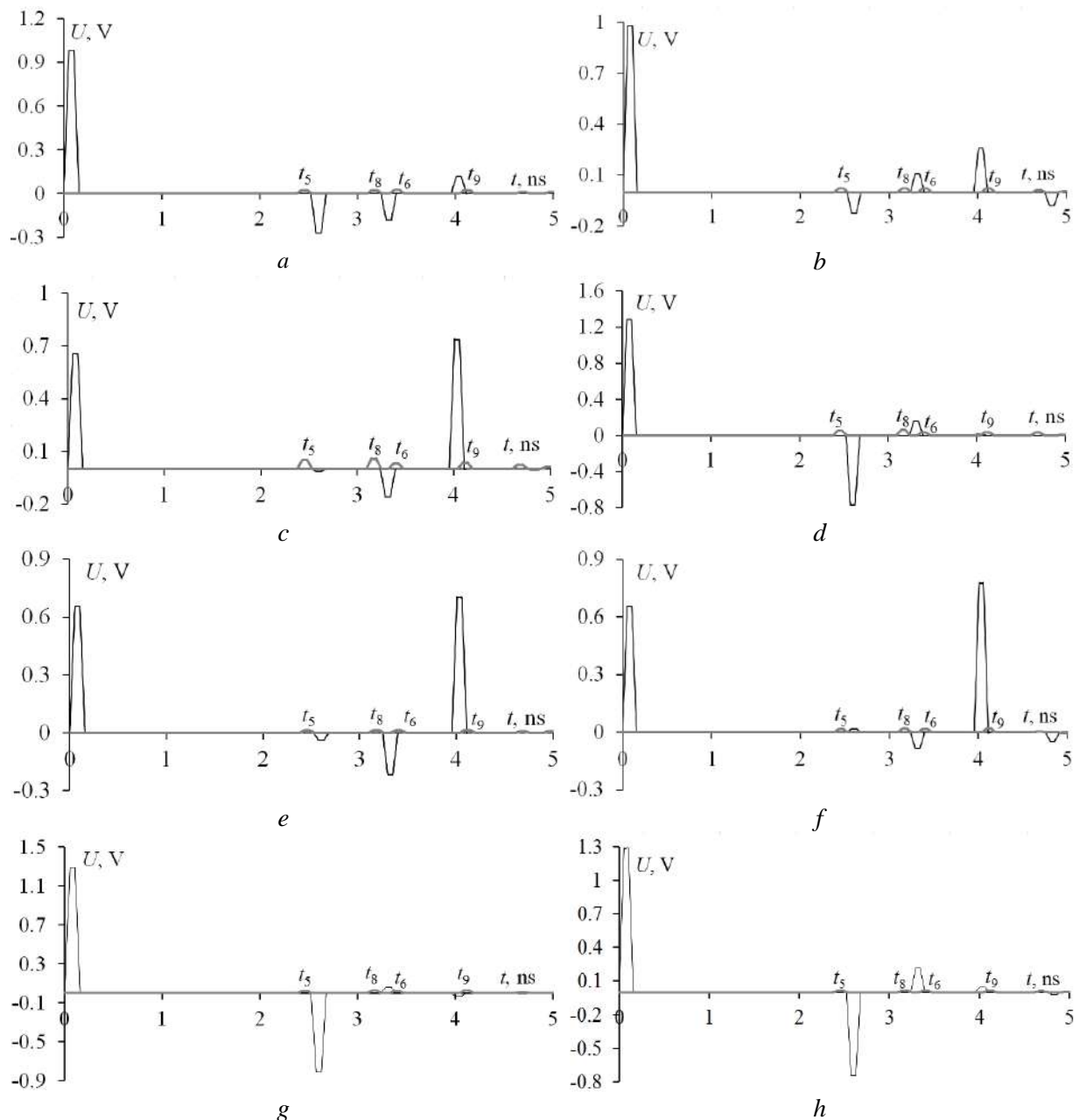


Figure 3. Voltage waveforms at the MF1 input (–) and MF2 output (–) at 50-50, SC-OC (a), 50-50, OC-SC (b), SC-OC, 50-50 (c), OC-SC, 50-50 (d), SC-OC, SC-OC (e), SC-OC, OC-SC (f), OC-SC, SC-OC (g), OC-SC, OC-SC (h).

4. Conclusion

Thus, the study shows the possibility of decomposing a USP in a serial connection of two MFs of the same length, with the implementation of the passive conductor in the cutout of the reference plane. The decomposition was achieved by increasing the coupling between the conductors of the MF2, which increases the difference in modal delays. The amplitude at the output was reduced by 12.5 times in relation to the half of the e.m.f. with 50 Ω resistors at the ends of the passive conductors. The influence of boundary conditions at the ends of the passive conductors of two MFs was considered. For OC-SC, OC-SC the amplitude reduction by 70 times was achieved. The results obtained make further research into the cascading of such MFs relevant.

Acknowledgments

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