Research of the New Structure of Reflection Symmetric Modal Filter

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Abstract – **The paper considers the protection of radio-electronic equipment against ultrashort pulses (USP) by means of modal filters (MFs). The new structure of reflection symmetric MF structure is analyzed. It is reflection symmetric MF with an internal two-layer reference conductor. The results of a quasi-static and electrodynamic analysis of the reflection symmetric MF under influence of the USP, without and with taking into account the losses are presented. Consistency of results are obtained. The results are useful for further research, since the implementation of the reflection symmetric MF in such configuration is appropriate for further implementation.**

Index Terms – **protection device, reflection symmetric modal filter, multiconductor line, modal filtration.**

I. INTRODUCTION

CURRENTLY, THE IMPORTANCE of ensuring the immunity of radio-electronic equipment (REE) to electromagnetic interference is growing up. Increasingly, there are cases when, under certain circumstances, the correct functioning of REE is impossible, while this fact is unacceptable for critical systems. Therefore, it is important to carefully observe electromagnetic compatibility (EMC) in the process of designing such systems. Meanwhile, one of the directions of EMC is protection against conducted interference that is electromagnetic interference penetrating the equipment directly through conductors [1]. A powerful ultrashort pulse (USP) presents particularly dangerous exposure [2]. Due to the wide range and high power, such USPs are able to penetrate the most diverse REE and disable it. Taking into account the peculiarities of the time and energy characteristics of USPs of various nature in the conditions of a modern electromagnetic environment, traditional methods of restriction and filtering are often ineffective or insufficient, which, in turn, requires the use of additional measures for the protection of REE.

Traditional devices are used as a protection against impulse interference, for example, voltage suppressors, varistors, passive RC- and LC-filters. However, such protecting devices have a number of disadvantages (low radiation resistance, short service life, failure to operate at high voltages, insufficient operating speed, etc.), making it difficult to protect against powerful USP.

A new devices based on modal filtration technology [3] have been proposed to protect against USP, which are devoid of these disadvantages and also have several advantages (absence of semiconductor components, as a result, high radiation resistance, long service life, operation at high voltages, small dimensions and low cost). There are various configurations of such devices [4], including coupled line, multiconductor, reflection symmetric modal filters (MF).

This paper considers MF with symmetry [5]. The original version of the reflection symmetric MF is a three-layer printed circuit board whose cross section is shown in Fig. 1. The implementation of such configuration is difficult because it does not satisfy the standard technological process of multilayer printed circuit boards manufacturing [6]. Meanwhile, the development of the reflection symmetric modal filter's configuration, which is more easy to implement, is highly relevant. The aim of this paper is to perform such study.

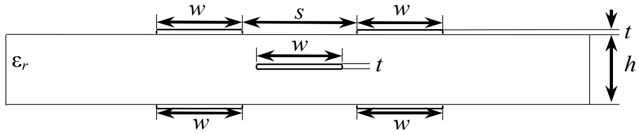

Fig. 1. Cross section of the original reflection symmetric MF

II. SIMULATION APPROACHES, SCHEMATIC DIAGRAM AND STRUCTURE OF MF

Traditionally, electrodynamic and quasistatic approaches are used in simulation of protective devices [7]. In electrodynamic simulation, Maxwell equations are solved. In this case, all types of waves are taken into account, which allows increasing the accuracy of calculations, but also leads to high computational costs, even when modeling elementary configurations. Hence, the electrodynamic approach is mainly used to model structures at high frequencies. While using the quasistatic approach, only the cross T-wave propagation is assumed, with the higher types of waves not being taken into account. The description of wave processes in the quasistatic approach is based on the telegraph equations, which Maxwell's equations are reduced to. The solution of these equations is less expensive, and the accuracy ensured by this approach is acceptable, even for solving complex problems [8].

Per unit length parameters and responses were calculated using quasistatic approach in TALGAT software [9]. Also, to confirm the results obtained by quasistatic analysis, an

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additional electrodynamic approach was used. It was assumed for quasistatic analysis that a transverse electromagnetic wave is propagating along the MF. As a pulse excitation we used the ideal EMF source with amplitude – 5 V with durations of rise, fall and flat top of 50 ps each, with the total duration of 150 ps. Loads at all conductor ends R=50 Ω, length of the line l=1 m. Schematic diagram for this MF is presented in Fig. 2.

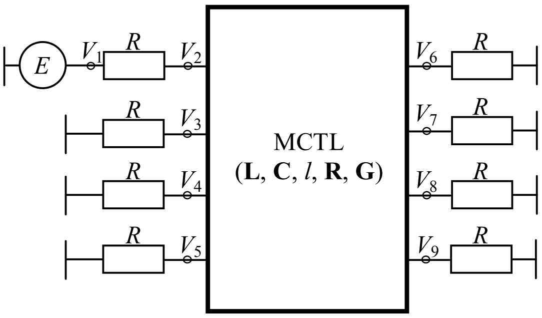

Fig. 2. Schematic diagram of reflection symmetric MF

Cross section of the new reflection symmetric MF is presented in Fig. 3, and its three-dimensional image is presented in Fig. 4, where w – the width of the conductors, s – the separation between conductors, t – the thickness of conductors, h – the thickness of the dielectric, h_1 – the height of the vias, g – the diameter of the vias. To simplify the construction of prototypes and accelerate the calculations, the stack and prepregs of the printed circuit board are represented by a homogeneous material with the relative dielectric permittivity ε_r=4.5 and dielectric loss tangent tgδ=0.025. When simulating without losses, entries of matrices **R** and **G** were accepted to be equal to zero. While taking into account the losses for calculating the per unit length entries of the matrix **G**, a widely known model of the frequency dependence of relative permittivity and tangent of the dielectric loss angle of FR-4 material are used [10]. The per unit length entries of the resistance matrix **R** were calculated taking into account the skin effect, the proximity effect and losses in the conductor by means of the method proposed in [11], implemented in TALGAT [12].

The new structure of the reflection symmetric MF implies a four-layer structure, where the first and fourth (external) layers – the reflection arranged pair of coupled lines, and the second and third (internal) layers – two ground conductors connected by regularly spaced vias to form a single ground.

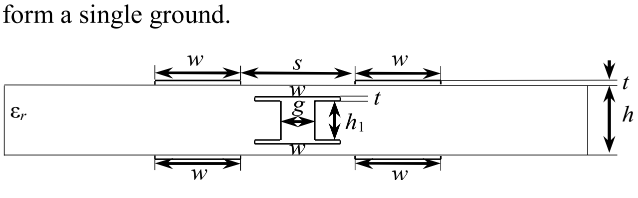

Fig. 3. Cross sections of the new reflection symmetric MF

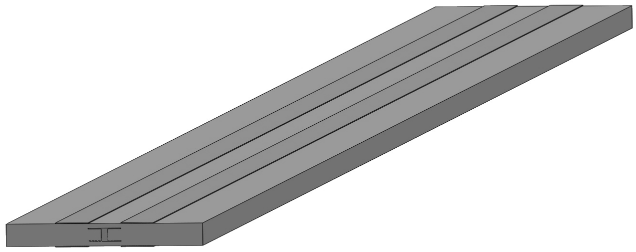

Fig. 4. Three-dimensional image of new reflection symmetric MF

III. Simulation Results

The MFs was simulated with the following parameters: s=700 μm, w=1000 μm, g=200 μm, t=35 μm, h=920 μm, h_1=510 μm. Parameters t, h, h_1 are standard in the manufacturing of four-layer printed circuit boards. Technologically implemented value of g can vary from 50 μm to 950 μm. Therefore, a value of 200 μm is chosen, which lies within these limits. Values of parameters w and s were obtained after optimization by three criteria: the minimization of MF's output voltage, the equalization of the differences between delays of decomposition pulses and the matching with 50 Ω impedance. Matrices of per unit length coefficients of electrostatic (**C**, pF/m) and electromagnetic (**L**, nH/m) inductions, respectively:

$$\begin{bmatrix} 130.46 & -4.80 & -29.08 & -1.73 \\ -4.80 & 130.46 & -1.73 & -29.08 \\ -29.08 & -1.73 & 122.76 & -5.22 \\ -1.73 & -29.08 & -5.22 & 122.76 \end{bmatrix}; \begin{bmatrix} 309.96 & 53.74 & 76.16 & 37.44 \\ 53.74 & 309.96 & 37.44 & 76.16 \\ 76.16 & 37.44 & 328.04 & 61.49 \\ 37.44 & 76.16 & 61.49 & 328.04 \end{bmatrix}.$$

The voltage waveforms at the output of the new reflection symmetric MF for quasistatic and electrodynamic approaches are presented in Fig. 5, and frequency dependencies of $|S_{21}|$ – in Fig. 6. Values of the amplitudes of the decomposition pulses, and the per unit length time delays of each pulse for quasistatic and electrodynamic analysis, without taking into account the losses are summarized in Table I and with taking into account the losses – in Table II.

Table I shows acceptable deviations (for pulse amplitudes – 7.3%, and for delays – 1.3%). The reasons why the forms of the decomposition pulses and the values of the per unit length delays calculated by means of the approaches differ primarily result from the different ways of considering the frequency dependences of ε_r and tgδ. In addition, radiation losses, which are not considered in the quasistatic approach, have an effect. Note that in Table II the values of the per unit length delays of decomposition pulses are not presented since in the simulation with taking account the losses, the partial overlapping of pulses (due to dispersion) makes them difficult to estimate and to obtain accurate values.

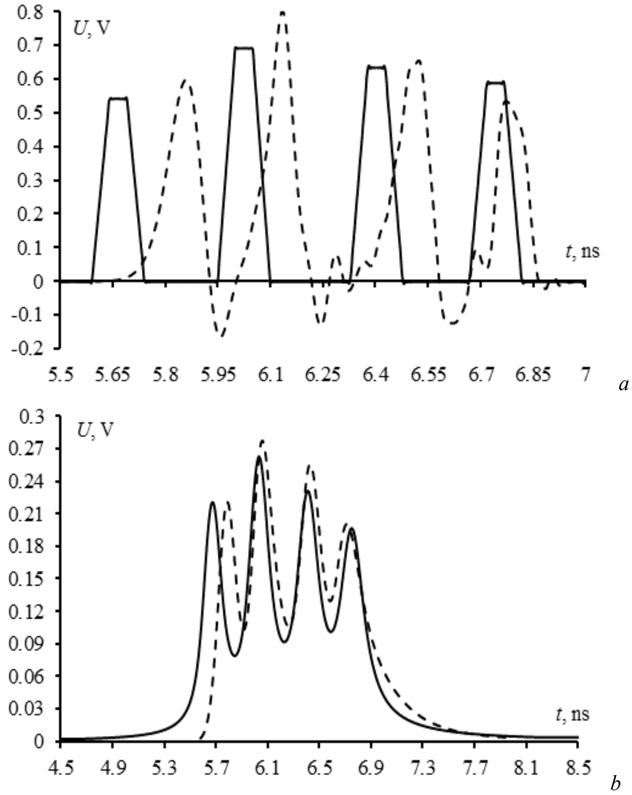

Fig. 5. Voltage waveforms at the output of active line under quasistatic (—) and electrodynamic (- -) approaches without (*a*) and with (*b*) taking into account the losses

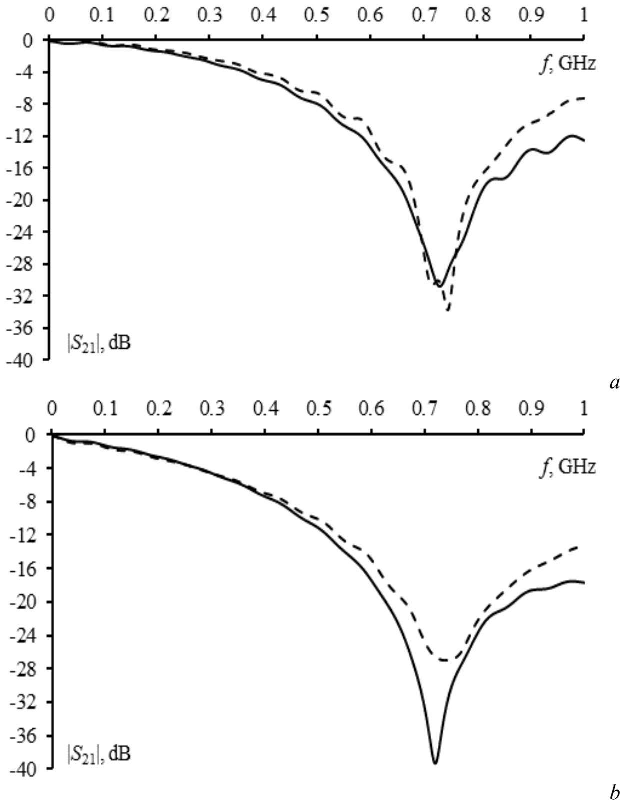

Fig. 6. Frequency dependencies of $|S_{21}|$ of reflection symmetric MF under quasistatic (—) and electrodynamic (- -) approaches without (*a*) and with (*b*) taking into account the losses

TABLE I

COMPARISON OF AMPLITUDES (U), PER UNIT LENGTH DELAYS (τ) OF FOUR PULSES, AND ALSO CUT-OFF (f_c) AND RESONANCE (f_r) FREQUENCIES FOR DIFFERENT TYPES OF ANALYSIS WITHOUT TAKING INTO ACCOUNT THE LOSSES

Parameter	Quasistatic	Electrodynamic	Deviation, %
U_1, V	0.543	0.587	3.89
U_2, V	0.692	0.801	7.31
U_3, V	0.639	0.654	1.16
U_4, V	0.593	0.534	5.23
τ_1, ns/m	5.591	5.741	1.32
τ_2, ns/m	5.949	6.001	0.44
τ_3, ns/m	6.327	6.372	0.36
τ_4, ns/m	6.667	6.721	0.41
f_c, GHz	0.317	0.350	4.94
f_r, GHz	0.731	0.746	1.02

TABLE II

COMPARISON OF AMPLITUDES (U) OF FOUR PULSES, AND ALSO CUT-OFF (f_c) AND RESONANCE (f_r) FREQUENCIES FOR DIFFERENT TYPES OF ANALYSIS WITH TAKING INTO ACCOUNT THE LOSSES

Parameter	Quasistatic	Electrodynamic	Deviation, %
U_1, V	0.220	0.221	0.23
U_2, V	0.262	0.277	2.78
U_3, V	0.231	0.255	4.94
U_4, V	0.196	0.201	1.26
f_c, GHz	0.227	0.218	2.02
f_r, GHz	0.721	0.740	1.30

The data obtained by simulation taking into account the losses in conductors and dielectrics (Table II) are also consistent. Fig. 5 (*b*) shows that for the quasistatic analysis, non-causality in the form of a premature arrival of a pulse signal is observed. It can be seen that in simulation without losses, the first pulse arrives at the end of the line at 5.6 ns, when the losses are taken into account, the time when the pulse arrives at the end of the line shifts to 4.6 ns. This is explained by the fact that the quasistatic analysis does not allow for adequate considering the frequency dependencies of ε_r and tgδ.

From the results of $|S_{21}|$ frequency dependence simulation it can be seen that the resonance frequencies in simulation by two different approaches also well coincided, differing only by 1% in simulation without taking losses into account and by 1.3% with taking into account the losses. There are different signal levels at the resonance frequencies. So, when modeling without losses, the deviation level is 4.5%, and taking into account the losses – 23.1%. The bandwidth, according to the results of the simulation using two approaches, is approximately 300 MHz in the simulation without taking account the losses and 210 MHz in the simulation with taking account the losses.

IV. Conclusion

In this paper, we consider a structure that is symmetrical about two axes, which implies the equality of certain per unit length coefficients of matrices **L** and **C**. However, due to the relative complexity of the geometric form of the ground conductor, these coefficients are not equal. As a result, some simulation errors are obtained. For example, different values of the main diagonal elements and $C_{12} \neq C_{34}$, $C_{13} \neq C_{24}$ are obtained (as in matrix **L**). Meanwhile, when calculating the response, we used the matrices (with errors) that were previously calculated. Obviously it has some influence on the output MF voltage waveforms. It makes an additional contribution to the difference in the results obtained by different methods. However, a detailed research of the causes of such errors is beyond the scope of this paper.

Thus, the results of a research of a new structure of a four-layer reflection symmetric MF are considered for the first time in this paper. A comparison of simulation results using quasistatic and electrodynamic approaches is presented. The consistency of simulation results in the time and frequency domains by two different approaches was obtained. It is noteworthy that the studied design of the reflection symmetric MF is quite easy to implement, due to the standard four-layer configuration. Thus, further experimental implementation and conducting a full-scale experiment are appropriate.

It is important to note that, according to qualitative estimates, the parameters of the initial MF depend on a certain ratio of the broad-side and edge couplings between the conductors. Meanwhile, in the new structure, this ratio can be additionally changed by choosing the value of h_1. Thus, an increase in h_1 (with the remaining parameters being unchanged) will reduce the broad-side couplings more strongly than edge couplings. Detailed simulation of this is undoubtedly useful and will be performed in the future.

Acknowledgments

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