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Quasi-static analysis of a two-conductor modal filter with a thin passive conductor

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Abstract. The paper presents the results of the quasi-static analysis of a two-conductor modal filter with a thin passive conductor. The geometrical parameters of the structure under investigation were optimized using a genetic algorithm. The authors performed the quasi-static simulation in the time domain with and without losses. It revealed that with a significant reduction in the thickness of the passive conductor it is possible to preserve or improve the electromechanical properties of the modal filter. The authors showed that in the proposed configuration the difference of per-unit-length delays increased from 0.43 to 0.93 ns, and the maximum output voltage decreased from 501 to 498 mV.

1. Introduction

For the protection of on-board radio-electronic systems of the spacecraft from broadband conductive interferences, various circuitry and design solutions are used [1, 2]. However, due to the presence of parasitic parameters, many of them are found to be ineffective [3]. Interference filters based on passive RLC components (resistors, inductors, capacitors) have several disadvantages. In the field of microwave frequencies, the inter-turn capacitance of chokes and the inductance of pins do not allow for the effective protection electronic equipment from broadband interferences. Semiconductor filters have similar disadvantages, though less significant. Their parasitic parameters severely limit the speed of operation. Besides, the presence of a p-n junction reduces the overall operating life and decreases the radiation resistance of protection systems. Due to its high power, short duration, and wide range, the ultra-short pulse (USP) can penetrate deep into radio-electronic systems and disable them. To protect vulnerable circuits and elements from USPs, the devices based on the modal filtering principle are successfully used [4–6]. Figure 1 shows the equivalent switch-on circuit of a two-conductor modal filter (MF) and Figure 2 shows its cross-section with a classical and thin passive conductor.

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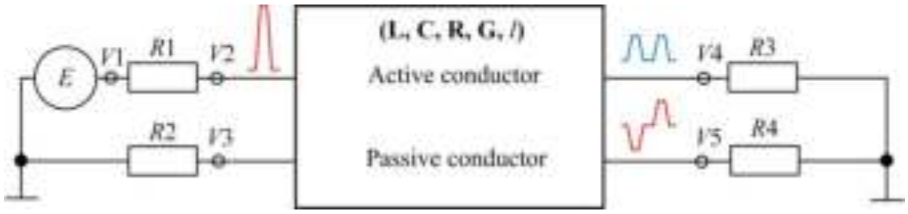

Figure 1. Equivalent circuit diagram of the two-conductor MF.

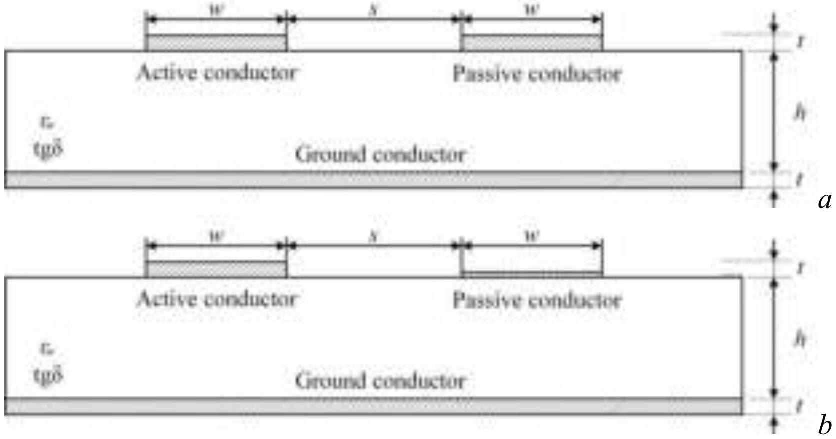

Figure 2. Cross-sections of the two-conductor MF
with the classical (*a*) and thin (*b*) passive conductors.

When passing through the MF, a USP is decomposed into two pulses of smaller amplitude. It should be noted that during the flow in the active DC conductor, the passive conductor is practically not activated. Moreover, in some applications, the presence of a passive conductor identical in height to the active one is not desirable. For example, the copper balance of the printed circuit board (PCB), its weight-size parameters and electromechanical characteristics may decrease. In the well-known works on modal filtration, the passive conductor was identical in height to the active one, and the influence of its thickness on MF characteristics has not been analysed. Thus, the purpose of this work is to fill this gap.

2. Approaches, methods and structures

Different approaches and methods are used to analyse noise protection devices. For example, the analysis of filters on the lumped elements, the schematic approach is successfully used [7]. For the analysis of filters on the elements with distributed parameters, quasi-static and electrodynamic approaches are used [8, 9]. In this work, we used the quasi-static approach, which provides sufficient accuracy at an optimal time spent on calculations. A numerical method for solving the integral equation was used, namely, the method of moments [10]. To obtain reliable results of modeling, the surface of a two-conductor MF was dynamically divided into segments inside of which surface charges were calculated (Figure 3). Thus, the number of segments on the smallest interval was not less than 8, which provides high accuracy of the results in the whole range of accepted values of *w* and *s*.

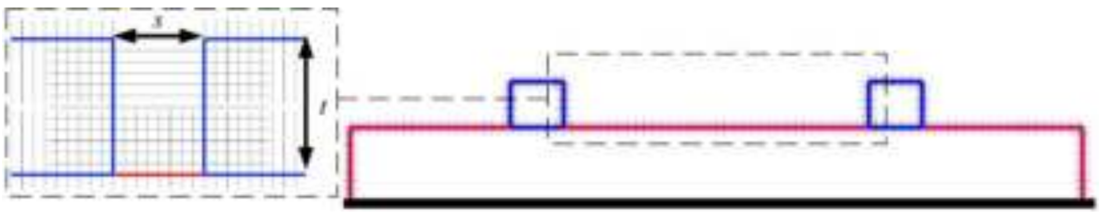

Figure 3. Segmentation in the simulation models of the two-conductor MF.

White ceramics Al_2O_3 96 % with dielectric constant $\varepsilon_r = 9.8$, loss tangent tgδ = 0.0004, $h = 0.5$ mm and $t = 300$ μm was chosen as a dielectric substrate material. The thickness of the passive conductor was 10 μm. In the process of simulation, dielectric and conductor losses were taken into account. The copper conductivity was 59,600 000 S/m. The initial parameters of the MF in the classical version were the following: $w = 350$ μm, $s = 2000$ mm, $l = 1$ m. The values of all resistances R were constant and accepted to be equal to 50 Ω.

3. Analysis of the influence of the passive conductor thickness on the MF characteristics

The voltage waveforms at the input ($V2$) and output ($V4$) of the two-conductor MF in the classical configuration are shown in Figure 4. We can see that the USP is divided into two pulses of smaller amplitude. The maximum amplitudes at the active line output of the two-conductor MF were 501 mV (without considering losses) and 454 mV (considering losses), and the difference of per-unit-length delays was 0.43 ns.

To analyse the influence of the passive conductor thickness on the two-conductor MF characteristics, the time responses at the near and far ends were obtained, the geometric mean value of the characteristic impedance along the main diagonal was calculated, the maximum voltage at the output of the active conductor was obtained, and the per-unit-length delays for even and odd modes were collected. The obtained results are presented in Table 1. The results show that as the thickness of the passive conductor decreases, the maximum voltage at the output of the active conductor increases. This is because the coupling between the active and passive conductors is weakened by the reduction in the thickness of the passive conductor. At the same time, it should be noted that the difference of per-unit-length delays increases. The characteristic impedance of the transmission line varies in a narrow range, so the absolute deviation is 4.35 Ω.

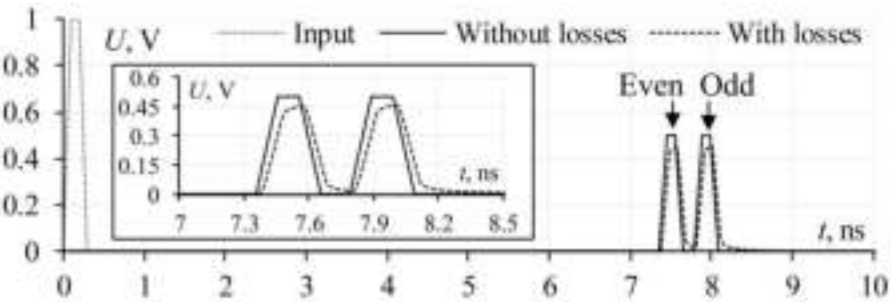

Figure 4. Input ($V2$) and output ($V4$) voltage waveforms of the two-conductor MF with a standard passive conductor.

Table 1. Influence of the passive conductor thickness on the two-conductor MF characteristics.

t, μm (pas. cond.)	Z, Ω	U_{max}, mV (without losses)	U_{max}, mV (with losses)	τ_1, ns/m	τ_2, ns/m	$\Delta\tau$, ns
300	50.014	501	454	7.357	7.791	0.434
250	50.478	567	526	7.392	7.815	0.423
200	51.005	647	610	7.426	7.848	0.423
150	51.614	730	690	7.458	7.894	0.437
100	52.342	812	765	7.487	7.960	0.473
50	53.265	881	818	7.513	8.056	0.543
10	54.372	927	827	7.530	8.160	0.629

4. Optimization of the two-conductor MF with a thin passive conductor

To obtain optimal parameters (w of passive conductors and s between conductors) in which the MF will be coordinated and the amplitude of the USP at the output of the two-conductor MF will be minimal. We performed the optimization by a global method (genetic algorithm) [11].

The two-conductor MF parameters optimized by the genetic algorithm are summarized in Table 2. After all iterations, the optimization of two-conductor MF parameters by the genetic algorithm was stopped. The optimal parameters for the configuration with the thin passive conductor were the following: $w = 670$ µm (active), $w = 250$ µm (passive), $s = 600$ µm. Figure 5 presents voltage waveforms of the investigated structure of the two-conductor MF with the thin passive conductor.

Table 2. Two-conductor MF parameters optimized by the genetic algorithm.

1	Number of individuals	50
2	Number of generations	50
3	Mutation Ratio	0.1
4	Crossover coefficient	0.5
5	Range of acceptable values for w (active conductor)	from 200 to 4000 µm
6	Range of acceptable values for w (passive conductor)	from 200 to 4000 µm
7	Range of acceptable values for s	from 200 to 4000 µm
8	Weighting ratios for two functions	0.5

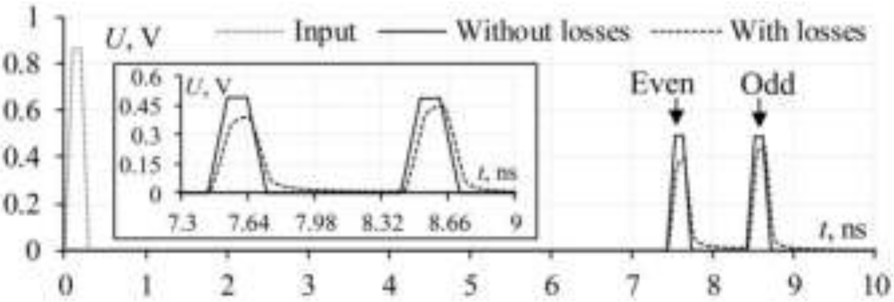

Figure 5. Input ($V2$) and output ($V4$) voltage waveforms of the two-conductor MF with the thin passive conductor.

The results show that the maximum amplitude at the output of the MF in the version with the thin passive conductor was 498 mV, and the difference of per-unit-length delays was 0.97 ns. Table 3 shows matrices **C** and **L** for the two-conductor MF in the classic configuration and the MF with the thin passive conductor.

Table 3. Matrices **C** and **L** for the two-conductor MF in different configurations.

Classic passive conductor	Thin passive conductor
$\mathbf{C} = \begin{bmatrix} 7.11028\cdot10^{-10} & -5.34505\cdot10^{-10} \\ -5.34505\cdot10^{-10} & 7.18458\cdot10^{-10} \end{bmatrix}$, F/m;	$\mathbf{C} = \begin{bmatrix} 7.02154\cdot10^{-10} & -4.31788\cdot10^{-11} \\ -4.31788\cdot10^{-11} & 6.13583\cdot10^{-10} \end{bmatrix}$, F/m;
$\mathbf{L} = \begin{bmatrix} 1.10911\cdot10^{-7} & 2.82698\cdot10^{-8} \\ 2.82698\cdot10^{-8} & 1.10998\cdot10^{-7} \end{bmatrix}$, H/m;	$\mathbf{L} = \begin{bmatrix} 1.16739\cdot10^{-7} & 2.47027\cdot10^{-8} \\ 2.47027\cdot10^{-8} & 1.34937\cdot10^{-7} \end{bmatrix}$, H/m.

5. Discussion

The decomposition of broadband conductive interferences by means of the modal filtration technology is an effective method of protecting radio electronic systems. The example of the two-conductor MF shows the decomposition of a USP into two pulses of the smaller amplitude corresponding to even and odd modes. By using ceramics with high ε_r, it is possible to obtain the difference in per-unit-length delays of 0.43 ns for the configuration of MFs with the identical conductors. However, when the thickness of the passive conductor decreases, the side coupling between the conductors degrades, which results in an increase in the maximum voltage at the far end of the active conductor. The optimization by the genetic algorithm was applied in this work to obtain optimal parameters of the MF structure with a thin passive conductor. The values of all optimized parameters were limited by the standard technological process in PCB manufacturing. As the optimization criteria, the authors chose the matching of the transmission line with the 50 Ω path and the minimization of the USP amplitude at the far end of the active line. The last criterion is achieved when the USP is decomposed into a sequence of pulses of smaller amplitude. Similar to the case with the classical MF configuration, in the version with a thin passive conductor, the USP is decomposed into two pulses. At the same time, comparing matrices **C** and **L** of both configurations we can see that mutual elements have changed the most. Thus, the change in the thickness of the passive conductor has little effect on the eigenvalues of **C** and **L** of the active conductor. In this case, this change greatly reduces the mutual influence of the active and passive conductors, which ultimately leads to an increase in the difference in per-unit-length delays (0.97 ns).

The results obtained agree well with the transmission line theory as well as with earlier computational and natural experiments. The reliability of the results obtained is conditioned by the accuracy of the quasi-static approach used, which shows the high accuracy of calculations. However, several limitations are accepted in the simulation process. For example, the values of ε_r and tanδ in the study are frequency independent, therefore, in real configurations this may result in additional dispersion. In addition, the study assumes that only the TEM wave propagates in the transmission line, and the influence of the higher-order modes is not taken into account, as well as the radiation losses. To obtain the most accurate results, it is necessary to apply electrodynamic analysis. To confirm the results of the simulation, it is necessary to conduct an experimental study on a real prototype. All this is a subject for subsequent studies. Nevertheless, the results show that the configuration of the MF with a thin passive conductor has all the interference protection properties of a classical MF. In this case, the mass of such a device will be cut down by the mass of the passive conductor. In general, the proposed method of designing the passive conductor of a two-conductor MF can improve its technical and operational characteristics.

6. Conclusion

The paper presents the results of the quasi-static analysis of the two-conductor modal filter with a thin passive conductor. The geometrical parameters of the investigated structure were optimized using a genetic algorithm. The authors performed the quasi-static simulation in the time domain with and without losses. It was revealed that with a significant reduction in the thickness of the passive conductor it is possible to preserve or improve the electromechanical properties of the modal filter. The paper demonstrated that in the MF with the thin passive conductor the difference of per-unit-length delays increased from 0.43 to 0.93 ns. At the same time and the maximum output voltage decreased from 501 to 498 mV.

Acknowledgments
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