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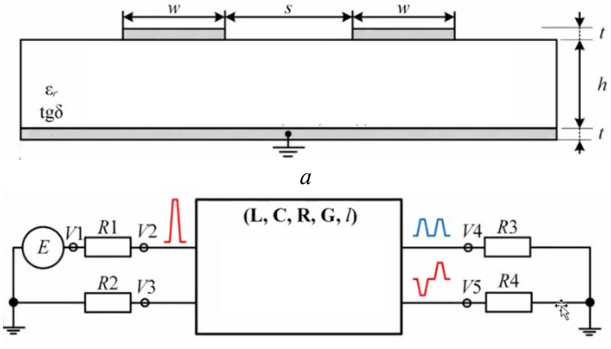
Two-wire modal filter with a thin passive conductor

The paper presents the results of quasi-static analysis of a two-wire modal filter with a thin passive conductor. The geometrical parameters of the investigated structure were optimized using a genetic algorithm. It is 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.

Keywords: modal filter, thin passive conductor, optimization, ultra-short pulse.

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]. Thus, 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 USP, the devices based on modal filtering principle are successfully used [4–6]. Fig. 1, *a* shows the cross-section of the two-wire modal filter (MF) in the classical configuration, and Fig. 1b shows its equivalent switch-on circuit. When passing through the MF, the 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. However, 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 PCB, its weight-size parameters and electromechanical characteristics may decrease. In the 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 was not analyzed. Thus, the purpose of this work is to fill this gap.



a

b

Fig. 1. Cross section of the two-wire MF (*a*) and its equivalent switch-on circuit (*b*)

Approaches, methods and structures

Different approaches and methods are used to analyze noise protection devices. Thus, for 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, the quasi-static approach is used, which provides sufficient accuracy at an optimal time spent on calculations.

A numerical method for solving the integral equation was used, namely, the moment method [10]. To obtain reliable results of modeling, the surface of a two-wire MF was dynamically divided into segments, inside of which surface charges were calculated (Fig. 2). 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*.

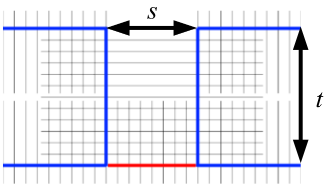


Fig. 2. Segmentation in simulation models of the two-wire MF

White ceramics Al_2O_3 96% with $\varepsilon_r = 9.8$, $h = 0.5$ 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 the simulation, dielectric and conductor losses were not taken into account. Initial parameters of MF in the classical version were: $w = 350$ μm, $s = 2000$ mm, $l = 1$ m. Values of all resistances *R* are a constant value and are accepted equal to 50 Ω.

Analysis of the influence of the passive conductor thickness on the two-wire MF characteristics

The voltage forms at the input (*V*2) and output (*V*4) of the two-wire MF in the classical configuration are shown in Fig. 3. We can see that the USP is divided into two pulses of smaller amplitude. The maximum amplitude at the active line output of the two-wire MF was 501 mV, and the difference of linear delays was 0.43 ns.

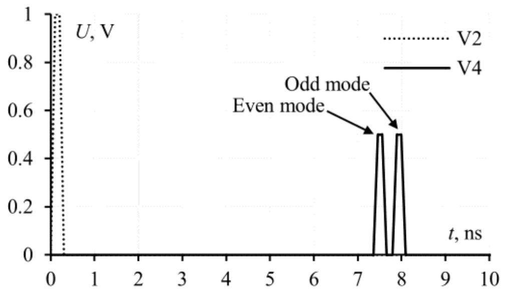


Fig. 3. Voltage forms at the input (*V*2) and output (*V*4) of a two-wire MF in a classic configuration

To analyze the influence of the passive conductor thickness on the two-wire 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 line 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 due to the fact that the connection 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 in per-unit-delay is increasing. The characteristic impedance of the transmission line varies in a narrow range, so the absolute deviation is 4.35 Ω.

Table 1

Analysis of the influence of the passive conductor thickness on the two-wire MF characteristics

t, μm (pas. cond.)	Z, Ω	$U_{\max}$, mV	τ_1, ns/m	τ_2, ns/m	$\Delta\tau$, ns
300	50.014	501	7.357	7.791	0.434
250	50.478	567	7.392	7.815	0.423
200	51.005	647	7.426	7.848	0.423
150	51.614	730	7.458	7.894	0.437
100	52.342	812	7.487	7.960	0.473
50	53.265	881	7.513	8.056	0.543
10	54.372	927	7.530	8.160	0.629

Optimization of two-wire MF in thin passive conductor configuration

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

The two-wire MF parameters optimized by the genetic algorithm are summarized in Table 2. After all iterations, optimization of two-wire MF parameters by the genetic algorithm was stopped. Optimal parameters for execution with thin passive conductor were: w = 670 μm (active), w = 250 μm (passive), s = 600 μm.

Table 2

Two-wire MF parameters optimized by the genetic algorithm

№	Parameters	Value
1	Number of individuals	50
2	Number of generations	50
3	Mutation Ratio	0.1
4	Crossover coefficient	0.5
5	Range of acceptance values for w (active conductor)	from 350 to 700 μm
6	Range of acceptance values for w (passive conductor)	from 300 to 4000 μm
7	Range of acceptance values for s	from 300 to 4000 μm
8	Weighting ratios for two functions	0.5

Fig. 4 presents voltage forms of the investigated structure of the two-wire MF in the version with a thin passive conductor.

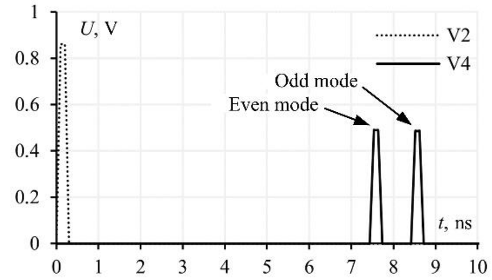


Fig. 4. Input ($V2$) and output ($V4$) voltage forms of two-wire MF with the thin passive conductor

The results show that the maximum amplitude of the MF in the version with a thin passive conductor was 498 mV, and the difference of per-unit-delay was 0.97 ns. The following are matrices **C** and **L** for the two-wire MF in a classic configuration, and for a MF with a thin passive conductor.

$$\mathrm{C}=\begin{bmatrix} 7.11028\cdot10^{-10} & -5.34505\cdot10^{-10} \\ -5.34505\cdot10^{-10} & 7.18458\cdot10^{-10} \end{bmatrix}, \text{ F/m;}$$

$$\mathrm{L}=\begin{bmatrix} 1.10911\cdot10^{-7} & 2.82698\cdot10^{-8} \\ 2.82698\cdot10^{-8} & 1.10998\cdot10^{-7} \end{bmatrix}, \text{ H/m;}$$

$$\mathrm{C}=\begin{bmatrix} 7.02154\cdot10^{-10} & -4.31788\cdot10^{-11} \\ -4.31788\cdot10^{-11} & 6.13583\cdot10^{-10} \end{bmatrix}, \text{ F/m;}$$

$$\mathrm{L}=\begin{bmatrix} 1.16739\cdot10^{-7} & 2.47027\cdot10^{-8} \\ 2.47027\cdot10^{-8} & 1.34937\cdot10^{-7} \end{bmatrix}, \text{ H/m.}$$

Conclusion

The paper presents the results of quasi-static analysis of a two-wire modal filter with a thin passive conductor. The geometrical parameters of the investigated structure were optimized using a genetic algorithm. It is 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.

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