Designing a low-mass, high-current modal filter for the spacecraft power bus

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Abstract. The paper presents the results of a quasi-static simulation of a modal filter with a reduced cross-section of conductors that are conducting a significant current. Time characteristics in differential and common modes are considered. The dependence of the attenuation coefficient on the thickness of the conductors is shown.

1. Introduction
Operation of electronic equipment in the outer space places high demands on its reliability. It is necessary to take into account the following factors: resistance to vibration, overloads, temperature drops, humidity, stability of parameters during the increase in the total dose of irradiation, and survival after the contact with heavy charged particles [1]. One of the urgent tasks is protection against electromagnetic interferences [2], among which an ultrashort pulse (USP) is particularly dangerous. Since its spectrum covers a wide frequency range, it is able to overcome traditional means of protection [3]. For the protection from USPs, it is worth mentioning a separate type of devices in which modal distortions are used [4]. Thanks to their design features, such devices are reliable and have a small mass although for space applications they should be even lighter.

The purpose of this work is to develop a USP protection device with a reduced mass, for a nominal current of 50 A, and which attenuates interferences in differential and common modes.

2. Designing a protective device
The proposed design is based on an asymmetric modal filter (MF) with a broadside coupling. It has a large difference in mode delays and a smaller output pulse amplitude than the edge-coupled MF. In the system of current-carrying parts of the MF, active conductors are critical nodes from the point of view of current carrying capacity. This is determined by the design features and requirements to such elements, which are specified during the design stage [5]. In accordance with GOST V 23584-79 [6], the calculation of the cross-sectional area of a current-carrying conductor is based on the permissible current density. The live parts of the MF, exposed to the current loads, are designed for a rated current of 50 A.
3. MF conductor configuration
To analyse the effect of the thickness of conductors that are not subject to significant currents, we performed a simulation with the following cross-sectional parameters: \( w = 10 \text{ mm}, \ w_1 = 20 \text{ mm}, \ s = 2 \text{ mm}, \ t = 1100 \mu \text{m}, \ t_1 = 35 \mu \text{m}, \ h = 330 \mu \text{m}, \ \varepsilon_{r1} = 1, \ \varepsilon_{r2} = 4.5. \) The length of the structure \( (l) \) was 150 mm. Cross-sections of MF structures of the original configuration and with a reduced mass are shown in Figure 1. A, P, R, R', A'

![Cross-sections of the original (a) and low-mass MF (b).](image)

4. Computer simulation of the MF
Computer simulation was performed in two versions, with and without losses in conductors and dielectrics. It was assumed that only the T-wave propagates in the MF. A single pulse with the duration of the front, fall and flat top of 100 ps each was used as a test excitation. The calculations of the matrixes of the electrostatic (C) and electromagnetic (L) inductions coefficients, as well as the waveforms, were performed in the TALGAT software. In addition, a quasi-static approach based on the method of moments was used. To increase the simulation accuracy, the most significant sections of the MF cross-section structure were divided into segments with the size of 30 \( \mu \text{m} \) for the original MF and 11 \( \mu \text{m} \) for the one with a reduced mass. Figure 2 shows a diagram of the MF electrical connections.

![MF electrical connection diagram.](image)

To simulate the differential mode, the MF was subjected to excitation pulses with an electromotive force (EMF) amplitude of 0.5 V for \( E_{S1} \) and -0.5 V for \( E_{S2} \). For the common mode, \( E_{S1} = E_{S2} = 1 \text{ V} \). The resistance values \( R_S \) and \( R_L \) were 50 Ohms.

5. MF mass calculation
The calculation of the MF mass was carried out on the basis of the density of the materials used and the parameters of the cross-section of the structure for the original and low-mass versions of the MF as
where $p_m$ and $p_{FR4}$ are the densities of copper and FR4 fiberglass, respectively. It is assumed that $p_m = 8.92 \text{ g/cm}^3$, and for $p_{FR4}$, which is in the range from 1.6 g/cm$^3$ to 1.9 g/cm$^3$, we used the average value. The mass was 125 g for the original MF and 39.52 g for the low-mass one. According to the calculation results, the weight of the MF was reduced by 3.16 times.

6. MF simulation results

In the simulation without taking into account losses in differential mode, the maximum output pulse amplitude was 75 mV for the original MF and 80 mV for the low-mass one, and in the common mode – 80 mV and 82 mV, respectively. Note that in all modes, the fourth pulse determines the maximum amplitude.

In the simulation with losses in differential mode, the maximum output pulse amplitude was 65 mV for the original MF and 69 mV for the low-mass one, and in the common mode – 70 mV and 70.5 mV, respectively. Note that in all modes, the fourth pulse determines the maximum amplitude.

**Figure 3.** Voltage waveforms at the output of the MF without losses in differential (a) and common (b) modes for $t_1 = 1100 \mu\text{m} (---)$, $35 \mu\text{m} (\cdots)$. 
Figure 4. Voltage waveforms at the output of the MF with losses in differential (a) and common (b) modes for $t_1 = 1100 \, \mu m$ (—), $35 \, \mu m$ (- -).

The calculated matrices for the original and low-mass configurations of the MF are given as:

$$
C = \begin{bmatrix}
1.27 & -1.23 & -9.77 \times 10^{-4} \\
1.23 & 1.27 & -3.6 \times 10^{-4} \\
-3.6 \times 10^{-4} & -3.52 \times 10^{-4} & 1.27
\end{bmatrix}
$$

$$
C = \begin{bmatrix}
1.27 & -1.23 & -2.2 \times 10^{-4} \\
1.23 & 1.27 & -11.5 \times 10^{-4} \\
-5.9 \times 10^{-4} & 1.27 & -1.23
\end{bmatrix}
$$

$$
L = \begin{bmatrix}
164 & 145 & 9.94 & 9.03 \\
145 & 162 & 10.9 & 9.94 \\
9.94 & 10.9 & 162 & 145 \\
9.03 & 9.94 & 164 & 162
\end{bmatrix}
$$

$$
L = \begin{bmatrix}
160 & 140 & 5.65 & 5.40 \\
140 & 159 & 5.92 & 5.65 \\
5.65 & 5.92 & 159 & 140 \\
5.40 & 5.65 & 160 & 160
\end{bmatrix}
$$

We obtained the dependence of MF attenuation coefficient ($K$) on the thickness of the conductors ($t_1$) that are not subject to significant currents (Figure 5).
Figure 5. Dependence of the MF attenuation coefficient on the thickness of the conductors in differential (—) and common (- -) modes.

It is known that as \( t_1 \) changes, the coupling coefficients between conductors also change. Figure 5 shows that with increasing \( t_1 \), with differential mode, the attenuation coefficient increases to 6.1, and with common mode - to 6. However, there is a value of \( t_1 \) (560 \( \mu \)m) at which the values of the attenuation coefficients take the same values. This is due to the peculiarity of the geometry of the filter cross section.

7. Conclusion

With a decrease in the thickness of conductors that are not subject to significant currents in differential and common modes, there is a slight decrease in the attenuation of the considered MF. For example, when the conductor thickness was changed from 1100 microns to 35 microns (31 times), which gave a decrease in the MF mass by 3.16 times, the attenuation coefficient of the MF decreased only by 8% for the differential mode, and by 3.5% for the common mode. Thus, the considered approach is reasonable.

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