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Parametric and structural optimization of the modal filter on a double-sided printed circuit board

M A Samoylichenko and T R Gazizov
Tomsk State University of Control Systems and Radioelectronics, 40, Lenina ave., Tomsk, 634050, Russia.

E-mail: 1993mary2011@mail.ru, talgat@tu.tusur.ru

Abstract. The effect of reducing the foil thickness and removing of one or two reference conductors in a modal filter on a double-sided printed circuit board is considered. The simulation of the ultra-short pulse propagation in such structures demonstrated that the signal is attenuated by 2 times in relation to half the e.m.f. when the foil thickness is 70 μm and by 3 times when the top left reference conductor is removed.

1. Introduction

Today’s radio electronic equipment (REE) is increasingly equipped with electronic control systems and microprocessor-based devices that are sensitive to electromagnetic interference. An increase in the degree of integration of the electronics element base leads to a decrease in the electrical strength of individual components of the equipment, as well as an increase in the vulnerability of REE elements to electromagnetic interference of different origins. In particular, ultrashort pulses (USPs) can lead to REE failure or malfunction [1].

The spacecraft onboard equipment is sensitive to USPs. In addition to general requirements (noise immunity, reliability, electromagnetic compatibility, etc.), a number of specific requirements are imposed on spacecraft onboard equipment: low mass, compactness, low power consumption, reliability under conditions of high temperatures, vibrations and overloads, immunity to penetrating radiation and low external pressure. Therefore, devices protecting against dangerous USPs, which are now being developed, must meet all these requirements. New protective devices called modal filters (MF) are the example of such devices [2]. They decompose an USP in a segment of a coupled line into modes each of which propagates with its own delay, so the MF output pulses have smaller amplitude. For example, such MF configurations as a multiconductor line, an interdigitated structure, a mirror-symmetric MF have been investigated [3-9]. However, they are difficult to integrate into double-side printed circuit boards (PCBs). This leads to the fact that they must be made as separate protective devices. Therefore, the search for new MF structures, which are free from this disadvantage, is relevant. One of the simple options for implementation is an MF cut in a double-sided PCB. It is noteworthy that for such an MF it is possible to lower the mass and to achieve the attenuation of the USP by reducing, for example, only the thickness of the conductors, but also by removing one or two reference conductors. The purpose of this work is to explore these possibilities.

2. Structure under investigation
Figure 1a shows the cross-section of the original MF with the following parameters: \( \varepsilon_r \) is the relative permittivity, \( w \) is the width of the conductors, \( t \) is the thickness of the conductors, \( h \) is the substrate thickness, \( s \) is the separation between the conductors. The foil-clad fiberglass (\( \varepsilon_r=4.5 \)) was chosen as the substrate material because of its low cost.

Optimization of MF parameters is performed according to the following criteria - the increase of the difference of the per-unit-length delays and the alignment of the USP amplitudes. This allows a uniform decomposition of the input influence with longer duration.

The MF connection diagram is shown in Figure 1a. The active conductor is connected to a pulse signal source, represented in the circuit as an ideal e.m.f. source \( E \) and internal resistance \( R1 \). The other end of the active conductor is connected to load \( R3 \). The resistance values \( R1, R2, R4, R5 \) were assumed to be the same and equal to 50 \( \Omega \). The input excitation was a trapezoidal pulse with parameters: the e.m.f. amplitude of 2 V; the rise, flat peak and fall times of 50 ps each. The parameters and waveforms were calculated using the quasistatic approach in the TALGAT software [10]. The losses in the conductors and dielectrics were not taken into account.

Since in this work the influence of \( t \), and the presence of reference conductors at this stage of the simulation \( h, w \) and \( s \) are chosen arbitrarily. The simulation was performed with \( h=500 \mu m \), \( w \) (for each conductor)=1000 \( \mu m \), \( s=300 \mu m \), MF length \( l \) of 1 m, \( t=105, 70, 35, 18 \mu m \). The calculated matrices of per-unit-length delay parameters for \( t=105 \mu m \) are the following:

\[
C = \begin{bmatrix}
139.7 & -21.36 & -21.36 & -79.62 & -8.754 \\
-21.36 & 118.2 & -2.198 & -8.734 & -1.246 \\
-21.36 & -2.198 & 118.2 & -8.734 & -84.80 \\
-79.62 & -8.734 & -8.734 & 139.8 & -21.31 \\
-8.754 & -1.246 & -84.80 & -21.31 & 118.3
\end{bmatrix}
\]

\[
L = \begin{bmatrix}
508.853 & 203.655 & 370.556 & 308.559 & 336.548 \\
20.655 & 352.76 & 183.281 & 149.265 & 169.73 \\
370.556 & 183.281 & 686.56 & 316.081 & 503.361 \\
308.559 & 149.265 & 316.081 & 454.295 & 336.375 \\
336.548 & 169.73 & 503.361 & 336.375 & 672.752
\end{bmatrix}
\]

The results of simulating the voltage waveforms at the MF input and output are shown in Figure 2. We can see that with \( t=105 \mu m \) (Figure 2a) and 70 \( \mu m \) (Figure 2b), 3 pulses are observed at the MF output. This is explained by the fact that the amplitudes of the first and fourth pulses are small. For \( t=35 \mu m \) (Figure 2c) and \( t=18 \mu m \) (Figure 2g) the amplitude of the first pulse becomes larger and it is clearly visible. The amplitude of the fourth pulse also becomes larger, but due to partial overlapping of the third pulse (for \( t=35 \mu m \) the difference of the per-unit-length is \( \tau_4-\tau_3=0.184 \) ns/m), it is almost unobservable. The amplitude of the fifth pulse (which is the maximum one) becomes lowest for \( t=70 \mu m \). The obtained values of per-unit-length delays and pulse amplitudes are given in Table 1.

**Table 1.** Per-unit-length delays (\( \tau, \) ns/m) and amplitudes (\( U, \) V) for different values of \( t \)

| \( t, \mu m \) | \( \tau_1 \) | \( \tau_2 \) | \( \tau_3 \) | \( \tau_4 \) | \( \tau_5 \) | \( U_1 \) | \( U_2 \) | \( U_3 \) | \( U_4 \) | \( U_5 \) |
|---|---|---|---|---|---|---|---|---|---|---|
| 105 | 4.199 | 4.597 | 5.786 | 5.941 | 6.411 | – | 0.208 | 0.306 | – | 0.494 |
| 70 | 4.353 | 4.744 | 5.721 | 5.931 | 6.474 | – | 0.233 | 0.326 | – | 0.428 |
| 35 | 4.382 | 4.924 | 5.811 | 5.995 | 6.477 | 0.016 | 0.220 | 0.285 | – | 0.480 |
| 18 | 4.418 | 4.939 | 5.858 | 6.024 | 6.497 | 0.009 | 0.223 | 0.286 | – | 0.478 |
Figure 2. Voltage waveforms at the MF input (–) and output (•) for $t=105$ (a), 70 (b), 35 (c) and 18 µm (d)

When the reference conductors were removed, the simulation was performed with the following parameters: $w=1000$ µm, $s=300$ µm, $h=500$ µm, $t=105$ µm. We considered four cases.
The cross section of the MF without the lower left reference conductor is shown in Figure 3a, and the connection diagram is shown in Figure 3b. The results of simulating the input and output voltage waveforms for such MF configuration are shown in Figure 4.

![Figure 3](image)

**Figure 3.** Cross section (a) and connection diagram (b) of the MF without the lower left reference conductor

The obtained values of per-unit-length delays and pulse amplitudes are given in Table 2.

| $\tau_1$ | $\tau_2$ | $\tau_3$ | $\tau_4$ | $U_1$ | $U_2$ | $U_3$ | $U_4$ |
|---------|---------|---------|---------|-------|-------|-------|-------|
| 4.399   | 4.751   | 5.736   | 6.358   | –     | 0.307 | 0.191 | 0.501 |

![Figure 4](image)

**Figure 4.** Voltage waveforms at the input (–) and output (−) of the MF without the lower left reference conductor

The cross section of the MF without the upper left reference conductor is shown in Figure 5, and the connection diagram is shown in Figure 3b. The results of simulating the input and output voltage waveforms for such MF are shown in Figure 6.

![Figure 5](image)

**Figure 5.** Cross section of the MF without upper left reference conductor

The obtained values of pulse amplitudes and per-unit-length delays are given in Table 3.

| $\tau_1$ | $\tau_2$ | $\tau_3$ | $\tau_4$ | $U_1$ | $U_2$ | $U_3$ | $U_4$ |
|---------|---------|---------|---------|-------|-------|-------|-------|
| 4.401   | 4.751   | 5.736   | 6.358   | 0.037 | 0.127 | 0.237 | 0.609 |
The cross section of the MF without the upper right reference conductor is shown in Figure 7, and the connection diagram is shown in Figure 3b. The results of simulating the input and output voltage waveforms of such MF are shown in Figure 8.

The obtained values of pulse amplitudes and per-unit-length delays are given in Table 4.

| $\tau_1$ ns/m | $\tau_2$ ns/m | $\tau_3$ ns/m | $\tau_4$ ns/m | $U_1$ V | $U_2$ V | $U_3$ V | $U_4$ V |
|---------------|---------------|---------------|---------------|--------|--------|--------|--------|
| 4.398         | 4.750         | 5.736         | 6.359         | 0.070  | 0.334  | 0.216  | 0.325  |

The presented results show that when one of the reference conductors is removed from the top, at the MF output we can observe 4 pulses, whereas when the lower reference conductor is removed, there are 3 pulses, which is explained by the small amplitude of the first pulse. The removal of the upper right reference conductor reduced the maximum amplitude. With $t=105$ $\mu$m and all reference conductors, the maximum amplitude is equal to 0.494 V, while when the right upper reference conductor is removed, the maximum amplitude is equal to 0.334 V. We can see that the best result is achieved when the right conductor is removed from the top, because $U_1=0.070$ V, $U_2=0.334$ V, $U_3=0.216$ V and $U_4=0.325$ V, and the differences in the per-unit-length delays are: $\tau_4-\tau_3=0.623$ ns/m, $\tau_3-\tau_2=1.236$ ns/m and $\tau_2-\tau_1=0.352$ ns/m. The removal of the left reference conductor, both upper and

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**Figure 6.** Voltage waveforms at the input (–) and output (•) of the MF without upper left reference conductor

**Figure 7.** Cross section of the MF without the upper right reference conductor

**Figure 8.** Voltage waveforms at the input (–) and output (•) of the MF without the upper right reference conductor
lower, only affects the amplitude. Thus, when removing the upper conductor, we get $U_1=0.037$ V, $U_2=0.127$ V, $U_3=0.237$ V and $U_4=0.609$ V, and when removing the lower one, we get $U_2=0.307$ V, $U_3=0.191$ V and $U_4=0.501$ V. The differences in the per-unit-length delays for two cases are the same and equal: $\tau_4-\tau_3=0.622$ ns/m, $\tau_3-\tau_2=0.985$ ns/m and $\tau_2-\tau_1=0.352$ ns/m.

At last, the cross section of the MF without two reference conductors is shown in Figure 9a and the connection diagram is shown in Figure 9b. The results of simulating the voltage waveforms at the MF input and output are shown in Figure 10. We can see that the input signal is decomposed into a sequence of two pulses.

The obtained values of per-unit-length delays and pulse amplitudes are given in Table 5.

**Table 5.** Per-unit-length delays ($\tau_i$, ns/m) and amplitudes ($U_i$, V) for the MF without two reference conductors diagonally

| $\tau_1$ | $\tau_2$ | $\tau_3$ | $U_1$ | $U_2$ | $U_3$ |
|----------|----------|----------|-------|-------|-------|
| 4.524    | 4.80013  | 6.20316  | –     | 0.160 | 0.817 |

**Figure 9.** Cross section (a) and connection diagram (b) of the MF without two reference conductors diagonally

**Figure 10.** Voltage waveforms at the input (–) and output (−) of the MF without two reference conductors diagonally

4. Conclusion

Thus, it is shown that by reducing the mass of the MF cut in the double-sided PCB it is possible to achieve greater attenuation of the USP. So, by reducing the conductor thickness to $t=70$ µm, we achieved the attenuation by 2 times in relation to half the e.m.f., and by removing the top right reference conductor - by 3 times. It is not insignificant that the considered variants of MF implementation allow to reduce mass (at the expense of removal of one reference conductor the mass of conductors is reduced in 1.6 times) that is actual and important in the onboard equipment of a spacecraft. The findings make further research on mass reduction in such MFs relevant. Also, to achieve the best result, it is reasonable to perform additional parametric optimization for each of the considered configurations.

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