

PAPER • OPEN ACCESS

Multicriteria optimization of a four-layer reflection-symmetric modal filter parameters for ESD protection

To cite this article: Y S Zhechev *et al* 2021 *J. Phys.: Conf. Ser.* **1862** 012023

View the [article online](#) for updates and enhancements.

A promotional banner for the 240th ECS Meeting. The banner features a colorful striped border at the top. On the left, the ECS logo is displayed in a green circle, followed by the text 'The Electrochemical Society' and 'Advancing solid state & electrochemical science & technology'. The main text reads '240th ECS Meeting' in large blue letters, with 'ORLANDO, FL' in smaller blue letters to its right. Below this, it says 'Orange County Convention Center' in orange and 'Oct 10-14, 2021' in blue. On the right side, there is a photograph of a large crowd of people. At the bottom, there is an orange bar on the left with the text 'Abstract submission deadline extended: April 23rd' and a blue bar on the right with the text 'SUBMIT NOW' in white.

ECS The Electrochemical Society
Advancing solid state & electrochemical science & technology

240th ECS Meeting ORLANDO, FL
Orange County Convention Center Oct 10-14, 2021

Abstract submission deadline extended: April 23rd **SUBMIT NOW**

Multicriteria optimization of a four-layer reflection-symmetric modal filter parameters for ESD protection

Y S Zhechev, I A Ivantsov and A M Zabolotsky

Department of Television and Control, Tomsk State University of Control Systems and Radioelectronics, 40 Lenin Avenue, Tomsk 634050, Russian Federation

E-mail: zhechev75@gmail.com

Abstract. The paper presents the results of a quasi-static analysis of a four-layer reflection-symmetric modal filter (MF) in the time domain. The authors analyzed its effectiveness in protecting electronic equipment against electrostatic discharge (ESD). The work presents the results of a genetic algorithm optimization of the geometric parameters of the structure under study. The results show that the investigated MF with optimal parameters can suppress the ESD peak emission at a shorter length.

1. Introduction

Modern radio-electronic equipment (REE) becomes more susceptible to various electromagnetic effects [1]. One of the current problems of electromagnetic compatibility is to protect electronics from the conducted interference of short duration [2], and in particular from ultrashort pulses (USP) and electrostatic discharge (ESD) [3]. Electromagnetic interference filters, isolators, interference suppressors, and discharge devices are traditional devices designed to protect against such interference. Meanwhile, constructive methods include grounding, stepping, as well as techniques for reducing power circuit impedances. In addition, to suppress conducted noise of short duration, there have been proposed devices based on modal filtering technology [4, 5]. Since signal modes in a transmission line have different phase propagation velocities, the pulse signal can be decomposed into a sequence of pulses of lower amplitude. One of the most effective devices based on this technology is a reflection-symmetric modal filter (MF). Several theoretical and experimental studies of such a device have been undertaken [6–8], but the evaluation of its efficiency in ESD suppression has not been carried out. Meanwhile, multicriteria optimization of such an MF for ESD protection is relevant since in the future, such an MF design can be used in signal and power circuits with redundancy, where ESD protection may be needed.

Thus, the purpose of this work is to perform multi-criteria optimization of the parameters of a four-layer reflection-symmetric MF intended for ESD protection.

2. Simulation and optimization methods

The authors utilized this quasi-static approach in the software package TALGAT [9]. When using a quasi-static approach, we assume the distribution of only the transverse T-waves, without considering the higher types of waves. Thus, the solution of Maxwell's equations is reduced to the telegraph equations, which allows performing this type of analysis much faster than the electrodynamic one. The accuracy of the quasi-static approach is acceptable even for solving complex problems [10].

We used a genetic algorithm (GA) for optimization [11, 12]. It is a heuristic search algorithm and performs well in search and optimization problems. The principle of GA operation is based on the theory



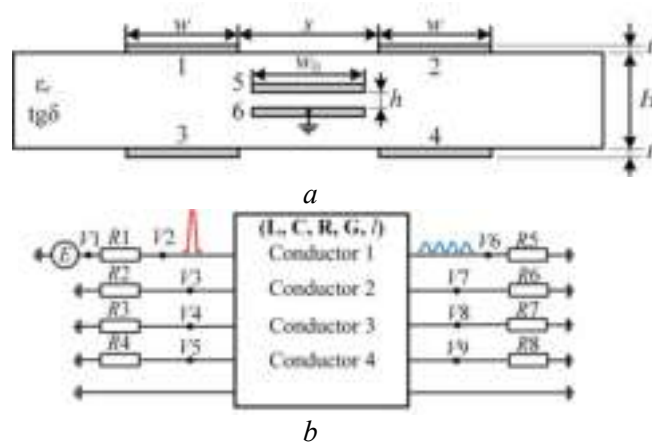


Figure 1. Cross-section (a) and equivalent circuit diagram (b) of the four-layer reflection symmetric MF.

of natural selection. During operation, the objective function of GA leads to the extremum point in the specified range of parameters by creating new populations - sets of solutions for the objective function obtained on the basis of the most successful solutions of previous generations. We performed optimization using the GA implemented in one of the modules of the TALGAT software. The use of quasi-static analysis models in the process of GA optimization can significantly speed up the process of optimization of multiconductor microstrip structures.

The MF (Figure 1) under investigation represents six identical and rectangular conductors on a dielectric layer. Conductors 1 and 2 are located on top side of it, additional conductors 3 and 4 are located reflection-symmetrically relative to conductors 1 and 2 on the bottom side of the dielectric layer. Reference conductors 5 and 6 are located inside the dielectric layer at an equal distance from the outer conductors and form a single ground. The MF under study, in the general case, is considered as a four-conductor transmission line with inhomogeneous dielectric filling. Therefore, four modes of the main type T-wave with their corresponding characteristics propagate in it.

The following parameters are initial for simulation: $w = 1000 \mu\text{m}$ is the width of the active and passive conductors, $w_0 = 1000 \mu\text{m}$ is the width of the reference conductor, $s = 700 \mu\text{m}$ is the distance between the conductors, $t = 35 \mu\text{m}$ is the conductors thickness, $h = 510 \mu\text{m}$ is the distance between the inner conductors, $H = 992 \mu\text{m}$ is the board thickness, $\epsilon_r = 4.5$ is the relative permittivity of the dielectric, $\text{tg}\delta = 0.025$ is the loss tangent of the dielectric (calculated for a frequency of 1 MHz). We used 50Ω resistors. The length of the initial structure is $l = 1 \text{ m}$. In the simulation, as the input excitation, we used an ESD current pulse corresponding to the third test level [13] and a USP with a total duration of 150 ps.

3. Study progress

The MF being investigated with parameters described previously is used for suppressing conducted interference of a short duration. Figure 2 shows the current waveforms at node V_6 under the excitation of a USP and an ESD on the MF. Figure 2(b) shows that the input pulse of a short duration is decomposed into 4 pulses of smaller amplitude. This ensures the protection of electronic equipment from USPs. However, Figure 2(a) shows that this configuration of the MF with $l = 1 \text{ m}$ fails to decompose the ESD because the condition from [14] is not satisfied. For the complete decomposition of the 100 ns ESD pulse, the MF must be at least 100 m in length. The weight and size parameters of the MF are not admissible; therefore, it is advisable to decompose only the first peak of the ESD pulse which has a duration of about 4 ns. For this, the initial MF length should be 4 m. The simulation results confirm this (Figure 2(b)); however, due to the losses, the pulses are overlapping.

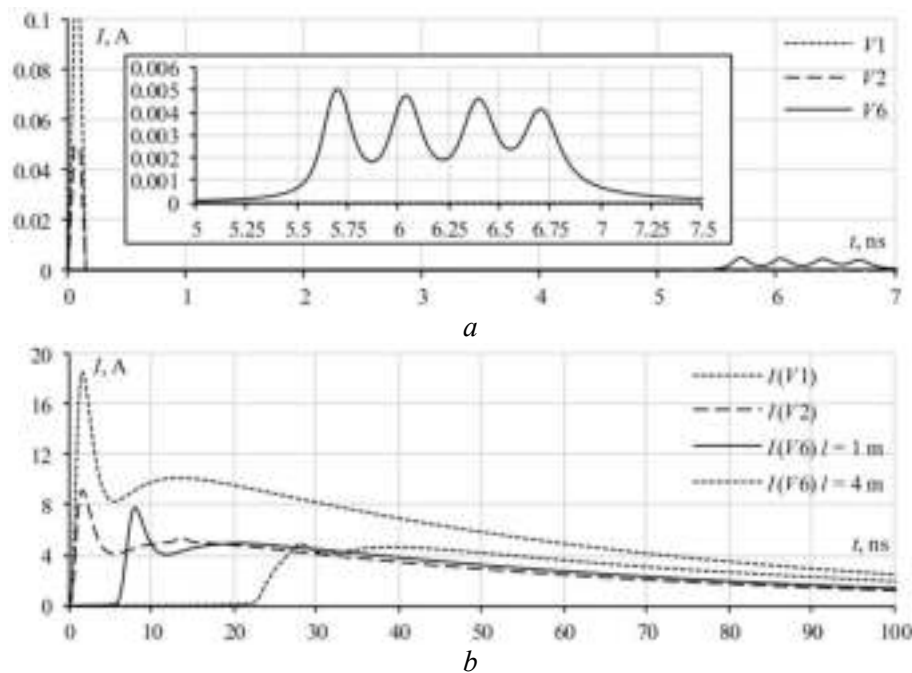


Figure 2. Current waveforms at $V6$ under the influence of USP (a) and ESD (b) on the MF.

To reduce the weight and size parameters of the MF that suppresses the first ESD pulse, we need to reduce the thickness of the board. However, there are some limitations associated with the breakdown in dielectrics. The dielectric strength of the material FR-4 used in the study is 50 kV/mm. Thus, to prevent breakdown inside the filter, the thickness of the dielectric layer must be greater than 20 μm . The use of materials with a higher permittivity of dielectrics will increase the difference of per-unit-length delays, which will consequently increase the MF efficiency. Table 1 shows the materials used for the printed circuit board (PCB) core and prepreg.

Table 1. Geometrical and dielectrical parameters of PCB materials.

| Core material | | | | | | |
|-------------------|-------------------------------------|------------------------------------|----------------------------------|--------------|-------------------|--|
| Type | Dielectric thickness, μm | Conductor thickness, μm | Overall thickness, μm | ϵ_r | $\text{tg}\delta$ | |
| Arlon AD1000 | 508 | 18 | 544 | 10.2 | 0.0023 | |
| Prepreg materials | | | | | | |
| 1080 (Tg170)x3 | 206 | 35 | 241 | 4.2 | 0.025 | |
| 2116 (Tg170) | 125 | 35 | 160 | 5.1 | 0.025 | |
| 1080 (Tg170) | 69 | 35 | 104 | 4.2 | 0.025 | |

GA optimization allows reducing the line length required to suppress the first ESD pulse. The objective function of GA is the sum of weighted and normalized criteria and has the form

$$F = \sum_i M_i \frac{f_i}{K_i} \rightarrow \min. \quad (1)$$

When optimizing the authors have chosen the coefficients K_i equal to the maximum value of the i_{th} objective function to the value of f_i/K_i takes a value from 0 to 1. In this case, the weights M_i we define the importance of the i_{th} criterion. If the criteria are equal, then these coefficients are the same [12].

We have chosen the following optimization criteria:

1. Minimization of the maximum output voltage:

$$f_1 = \max U(V6), \quad (2)$$

$$K_1 = \max U(V2). \quad (3)$$

2. Alignment of delays between decomposition pulses:

$$f_2 = \max |\tau_i - (\tau_{\min} + (i - 1)\Delta)|, \quad (4)$$

$$K_2 = \frac{\sqrt{\varepsilon_{r \max}} - 1}{c}. \quad (5)$$

3. Matching of the MF with a 50 Ω

$$f_3 = |\max U(V1) - 2\max U(V2)|, \quad (6)$$

$$K_3 = \max U(V1). \quad (7)$$

During optimization, we set the following GA parameters: the number of individuals – 40, the number of generations – 150, the mutation coefficient – 0.1, the crossover coefficient – 0.5. For a given number of individuals and generations, the maximum standard deviation σ of the objective function is 0.138 and 0.103 for optimization by two and three parameters, respectively.

4. Simulation results

In this work, the authors optimized 4 configurations of the MF: the first - with standard dielectric materials, the rest - with dielectric materials from Table 1. For each configuration, we carried out optimization in 2 sets of parameters, where the first set of parameters was: s from 200 μm to 2000 μm , w from 200 μm to 2000 μm ; the second set of parameters was: s from 200 μm to 2000 μm , w from 200 μm to 2000 μm , w_0 from 200 μm to 2000 μm . For each set of parameters, we conducted 5 launches of the GA and chose the best result. Tables 2 and 3 show the optimization results for the first and second sets of parameters, respectively. For each set, the following values are presented: the maximum output voltage, the average arithmetic value of the elements of the characteristic impedance matrix over the main diagonal, the current attenuation, the difference of per-unit-length delays multiplied by l .

Table 2. Optimization results for s, w .

| Configuration | Number of launch | $s, \mu\text{m}$ | $w, \mu\text{m}$ | $U_{out \max}, \text{V}$ | Z, Ω | $I_{out \max}, \text{A}$ | $ \tau_{\max} - \tau_{\min} , \text{ns}$ |
|---------------|------------------|------------------|------------------|--------------------------|-------------|--------------------------|--|
| 1 | 5 | 203 | 649 | 229.07 | 50.59 | 4.52 | 5.80 |
| 2 | 2 | 200 | 617 | 228.303 | 51.05 | 4.47 | 6.36 |
| 3 | 3 | 204 | 378 | 221.086 | 49.98 | 4.42 | 6.6 |
| 4 | 4 | 200 | 289 | 214.025 | 49.12 | 4.35 | 4.76 |

Table 3. Optimization results for s, w and w_0 .

| Configuration | Number of launch | $s, \mu\text{m}$ | $w, \mu\text{m}$ | $w_0, \mu\text{m}$ | $U_{out \max}, \text{V}$ | Z, Ω | $I_{out \max}, \text{A}$ | $ \tau_{\max} - \tau_{\min} , \text{ns}$ |
|---------------|------------------|------------------|------------------|--------------------|--------------------------|-------------|--------------------------|--|
| 1 | 5 | 305 | 829 | 685 | 230.24 | 49.91 | 4.64 | 5.51 |
| 2 | 2 | 277 | 798 | 533 | 229.404 | 52.4 | 4.37 | 6.72 |
| 3 | 2 | 277 | 798 | 533 | 229.404 | 52.4 | 4.37 | 6.72 |
| 4 | 4 | 202 | 403 | 234 | 215.144 | 50.12 | 4.29 | 5.44 |

Figure 3 shows the current waveforms at the output of the initial and optimized configurations of the investigated MF for $l = 4 \text{ m}$, as well as the dependence of I_{\max} on l . Table 4 shows the minimum MF length necessary to suppress the first ESD pulse with the optimal parameters.

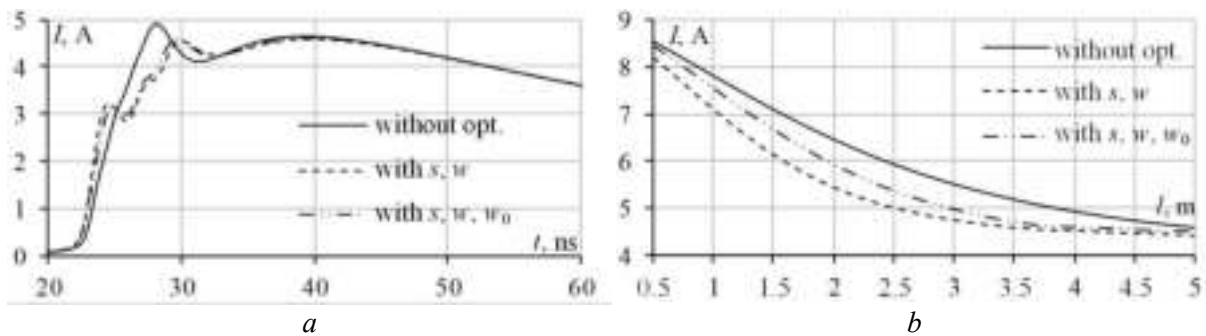


Figure 3. Current waveforms at the output of the initial and optimized MF configurations with standard materials for $l = 4$ m (a), and the dependence of I_{\max} on l (b).

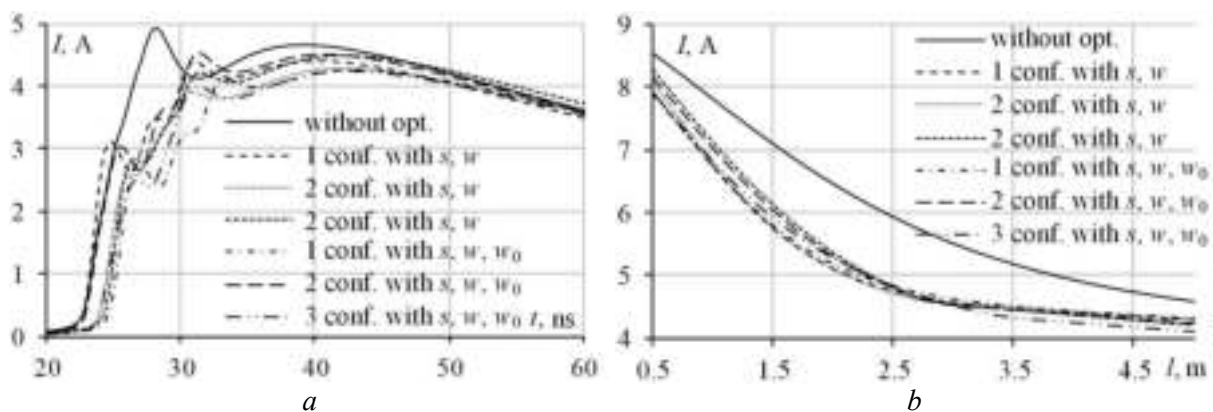


Figure 4. Current waveforms at the output of the initial and optimized MF configurations with modified materials for $l = 4$ m (a), and the dependence of I_{\max} on l (b).

Table 4. Minimum MF length sufficient to suppress the first ESD pulse with optimal MF parameters.

| Type of optimization | Number of configuration | l , m | U_{\max} , V | I_{\max} , A | $ \tau_{\max} - \tau_{\min} $, ns/m |
|----------------------|-------------------------|---------|----------------|----------------|--------------------------------------|
| - | Initial | 4 | 245.39 | 4.92 | 4 |
| s, w | 1 | 2.75 | 245.2 | 4.86 | 3.99 |
| | 2 | 2.54 | 245.28 | 4.73 | 4.07 |
| | 3 | 2.2 | 245.039 | 4.9 | 3.63 |
| | 4 | 2.3 | 245.053 | 4.99 | 2.74 |
| s, w, w_0 | 1 | 3 | 245.674 | 4.92 | 4.14 |
| | 2 | 2.7 | 245.169 | 4.73 | 4.58 |
| | 3 | 2.4 | 245.499 | 4.85 | 2.99 |
| | 4 | 2.49 | 245.144 | 4.89 | 3.25 |

The results show that the optimized configurations provide decomposition of the first ESD pulse at a shorter length than the initial configuration. Thus, with $l = 2.5$ m, the value of I_{\max} does not exceed 5 A for the configuration with unmodified dielectric materials (optimized s and w). For the configuration with modified dielectric materials, optimization of s and w gives the same result with $l = 2.0$ m. At the same time, the initial configuration shows a similar result only with $l = 3.9$ m.

5. Conclusion

Thus, in this paper, we performed the multicriteria optimization of the parameters of the four-layer reflection-symmetric MF according to the following criteria: ESD decomposition, wave impedance

matching, and equalization of the intervals between decomposition pulses. During the research, we found that in such MFs it is reasonable to decompose only the first pulse of an ESD. For the optimization without changing dielectric materials, the minimum length sufficient to suppress the first ESD pulse is 2.75 m (corresponds to optimization of s and w). In the optimization with a change in dielectric materials, this value is 2.2 m (corresponds to optimization of s and w for the third configuration). Further, after multicriteria optimization with a large number of optimized parameters, we are planning to carry out electrodynamic simulation, build a prototype of a reflection-symmetric MF as well as conduct experimental studies in the time and frequency domains.

Acknowledgments

The reported study was funded by RFBR, project number 20-37-90098.

References

- [1] Wei X C 2017 *Modeling and design of electromagnetic compatibility for high-speed printed circuit boards and packaging* (CRC Press)
- [2] Ott H W 2011 *Electromagnetic compatibility engineering* (John Wiley & Sons)
- [3] Violette N 2013 *Electromagnetic compatibility handbook* (Springer)
- [4] Gazizov A, Zabolotskii A and Gazizov T 2018 *Journal of Communications Technology and Electronics* **63** 270–276
- [5] Belousov A, Gazizov T and Zabolotsky A 2015 *Dokl. Tomsk. Univ. Sist. Upr. Radioelektr* **3** 124–128
- [6] Zhechev Y, Chernikova E, Belousov A and Gazizov T 2019 *Systems of Control, Communication and Security* 162–179
- [7] Chernikova E B, Belousov A O, Gazizov T R and Zabolotsky A M 2019 *Symmetry* **11** 883
- [8] Zhechev Y S, Chernikova E B and Belousov A O 2019 *2019 20th International Conference of Young Specialists on Micro/Nanotechnologies and Electron Devices (EDM)* (IEEE) 108–112
- [9] Kuksenko S 2019 *IOP Conference Series: Materials Science and Engineering* vol 560 (IOP Publishing) p 012110
- [10] Orlov P E and Buichkin E N 2017 *2017 18th International Conference of Young Specialists on Micro/Nanotechnologies and Electron Devices (EDM)* (IEEE) 54–58
- [11] Ahn C W 2006 *Advances in evolutionary algorithms* (Springer)
- [12] Belousov A O and Gazizov T R 2018 *Complexity* **2018**
- [13] Commission I E *et al.* 2003 *Electromagnetic compatibility (EMC)-Part 4*
- [14] Gazizov A T, Zabolotsky A M and Gazizov T R 2016 *IEEE Transactions on Electromagnetic Compatibility* **58** 1136–42