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Optimization of Multiconductor Modal Filters Using Various Criteria with Different Weighting Coefficients

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Abstract. The article considers the protection of radio-electronic equipment from ultrashort pulses (USP) by means of modal filters (MFs). The multiconductor microstrip MF structures are analysed. The results of multiconductor MF optimization using different criteria are presented. The amplitude and time criteria for optimizing an MF (with any number of conductors) are formulated in an analytical form, and a general multicriteria objective function for optimizing an MF using different criteria with different weighting coefficients is obtained.

1. Introduction

Today's radio-electronic equipment has extended functionality but, at the same time, it is susceptible to electromagnetic interference. Conducted interference is considered to be the most harmful one, as it can penetrate into devices directly through conductors [1]. Modern generators of ultrashort pulses have very high capabilities [2]. Such ultrashort pulses are able to penetrate and disturb the electronics due to the high power output and short duration. Therefore, it is necessary to do research into the new ways of improving the protection of electronics against ultrashort pulses.

One of the new protection principles is based on modal filtering – the use of modal distortions (signal changes caused by the difference in the mode delays of a multiconductor transmission line (MCTL)) – to provide protection of a device by means of sequential modal decomposition of the pulse in the segments of coupled lines. A series of research indicates the possibility of creating protective devices based on modal filtering – modal filters (MF) [3]. They can be radiation resistive, low mass, and cheap. As a device for protecting against pulse disturbances, one can use a microstrip structure based on a wide-spread foil-coated glass fibre sheet [4]. However, earlier research was aimed at MFs based only on a pair of coupled lines, while MFs based on multiconductor lines have gained interest only recently. Thus, the use of MCTL resources for an MF is relevant.

The creation of any new equipment often requires simulating complex systems and handling complex problems. For this purpose, optimization methods based on evolutionary algorithms are successfully used, for example, in power electronics [5] and applied electrodynamics [6]. Unfortunately, a number of trends in developing devices to protect against ultrashort pulses are also increasingly reduced to simulating complex systems.

A number of research have already been performed into a multiconductor microstrip MF. Paper [7] provides their brief review, and multicriteria optimization of a four-conductor microstrip MF using a matching criterion as well. However, in the previous studies, the weighting coefficients for multicriteria optimization of MFs remained unaddressed. In addition, multicriteria optimization of a three-conductor microstrip MF using a genetic algorithm (GA) with different weighting coefficients has not been performed before. Meanwhile, the possibility to highlight or neglect certain criteria is important for a user. Thus, it is desirable to carry out multicriteria optimization of a three-conductor microstrip MF with different weighting coefficients. The aim of this paper is to perform such research.

To do this, first (for the sake of completeness, using the results of [7]), let us present the formulation of the multicriteria objective function, as well as the amplitude and time optimization criteria. Then, let us provide the objective function for optimizing the three-conductor microstrip MF using four criteria. Finally, let us describe the test optimization of four parameters of a three-conductor MF with different weighting coefficients.

2. General formulation of a multicriteria objective function

The formulation of a multicriteria objective function (F) implies reducing separate criteria to a single problem of minimization or maximization:

$$F \rightarrow \min \text{ or } F \rightarrow \max. \tag{1}$$

For brevity, let usl consider the minimization. For example, the sum or the maximum of the weighted and normalized absolute values of the objective functions that formulate separate criteria can be minimized:

$$F = \sum_i F_i \text{ or } F = \max\{F_i\} \tag{2}$$

where

$$F_i = M_i \frac{f_i}{K_i} \tag{3}$$

where f_i is the objective function, K_i is a normalization constant, M_i is a weighting coefficient of i-th criterion, i=1, 2, …, N_C, where N_C is a number of optimization criteria.

Normalization coefficients K_i are chosen to be equal to the maximum possible value of the i-th objective function so that the value of f_i/K_i became dimensionless and took values from 0 to 1 during optimization. Moreover, K_i must guarantee non-negative values of F_i. The significance of the i-th criterion is given by the weighting coefficients M_i. If the criteria are of equal value to the user, then these coefficients are the same and can be given as:

$$M_i = \frac{1}{N_C}. \tag{4}$$

The optimization can be performed using various criteria. The amplitude and time criteria are relevant for the electrical characteristics of multiconductor MFs. They are discussed in detail in the subsequent sections.

3. Amplitude criteria

The most important criteria for optimization of an MF are amplitude ones. They can be considered in the time and frequency domains. It is useful to analyze the waveform $U(t)$ at the MF output to provide protection against the exciting ultrashort pulse of electromotive force $E(t)$. Therefore, let us consider the amplitude criteria in the time domain. On the basis of $U(t)$, five norms used to evaluate the effectiveness of an ultrashort pulse impact on different (depending on specific character of the response to the impact) equipment are distinguished [2]. Using these norms, one can formulate expressions for f_i and K_i.

1. For the circuit upset, as well as electric breakdown or arc-over effects, the maximum magnitude of the value of the $U(t)$ is important:

$$f_1 = \max|U(t)|, \ \ K_1 = \max|E(t)|. \tag{5}$$

2. For component arcing, as well as the circuit upset, the maximum magnitude of the $U(t)$ change rate is important:

$$f_2 = \max\left|\frac{\partial U(t)}{\partial t}\right|, \ \ K_2 = \max\left|\frac{\partial E(t)}{\partial t}\right|. \tag{6}$$

3. For dielectric puncture, the maximum magnitude of the integral of the $U(t)$ is important:

$$f_3 = \max\left|\int_0^t U(t)dt\right|, \ \ K_3 = \max\left|\int_0^t E(t)dt\right|. \tag{7}$$

4. For equipment damage, the integral of the $U(t)$ magnitude is important:

$$f_4 = \int_0^\infty |U(t)|dt, \ \ K_4 = \int_0^\infty |E(t)|dt. \tag{8}$$

5. For component burnout, the square root of the integral of the square of the $U(t)$ magnitude is important:

$$f_5 = \left\{\int_0^\infty |U(t)|^2 dt\right\}^{\frac{1}{2}}, \ \ K_5 = \left\{\int_0^\infty |E(t)|^2 dt\right\}^{\frac{1}{2}}. \tag{9}$$

4. Time criteria

Time criteria are important for preventing pulse overlaps that increase the maximum voltage at the MF output while increasing the duration of the exciting ultrashort pulse. In contrast to amplitude ones, time criteria may not require costly computation of the response, since it is enough to calculate only the per-unit-length delays. We consider three types of the time criteria.

The minimum-time criterion and the maximum-time criterion are associated with the expansion of the pulses time range at the MF output. The interval-time criterion is related to the equalization of time intervals. Note that in the time criteria, the values of the per-unit-length delay are ordered in ascending order.

The minimum-time criterion makes the per-unit-length delay of the first pulse ($\tau_{\min}$) as short as possible, i.e. determined by the light velocity in the vacuum:

$$f_6 = \tau_{\min} - \frac{1}{c}, \ \ K_6 = \frac{\sqrt{\varepsilon_{r\max}} - 1}{c}. \tag{10}$$

The maximum-time criterion makes the per-unit-length delay of the last pulse ($\tau_{\max}$) as long as possible, i.e. determined by the light velocity in the dielectric with the maximum value of the relative dielectric permittivity ($\varepsilon_{r\max}$):

$$f_7 = \frac{\sqrt{\varepsilon_{r\max}}}{c} - \tau_{\max}, \ \ K_7 = \frac{\sqrt{\varepsilon_{r\max}} - 1}{c}. \tag{11}$$

To expand the time range in both directions, these criteria must be used together. They are applicable to an MF with any number of conductors (N).

The interval-time criterion is important when N>2. It is used to equalize time intervals between the pulses at the MF output. It allows increasing the duration of the exciting ultrashort pulse, which will completely be decomposed at the MF output. For the values arranged by increasing per-unit-length delays, and based on the deviation of the current values of the per-unit-length delay of the intermediate modes from the values for case of equal time intervals between the pulses, let us obtain

$$f_8 = \max\left|\tau_i - \left(\tau_{\min} + (i-1)\cdot\Delta\right)\right|,\ i = 2,\ldots,N-1,\ K_8 = \frac{\sqrt{\varepsilon_{r\max}} - 1}{c} \tag{12}$$

where:

$$\Delta = \frac{\tau_{\max} - \tau_{\min}}{N-1} \tag{13}$$

where τ_i is a value of a per-unit-length delay of the *i*-th pulse.

5. Multicriteria GA optimization of a three-conductor MF

To test the theory, a three-conductor microstrip MF was optimized using the simple GA. The authors used the multicriteria objective function that combines one amplitude (5) and three (10–12) time criteria for *N*=3:

$$F = M_1\cdot\left(\frac{\max(U(t))}{\max(E(t))}\right) + M_2\cdot\left(\frac{\tau_1 - \frac{1}{c}}{\frac{\sqrt{\varepsilon_{r\max}}-1}{c}}\right) + M_3\cdot\left(\frac{\frac{\sqrt{\varepsilon_{r\max}}}{c} - \tau_3}{\frac{\sqrt{\varepsilon_{r\max}}-1}{c}}\right) + M_4\cdot\left(\frac{\left|2\tau_2 - \tau_1 - \tau_3\right|}{\frac{\sqrt{\varepsilon_{r\max}}-1}{c}}\right). \tag{14}$$

A GA is an evolutionary algorithm, with the main point of using the ideas of evolutionary theory to solve optimization problems. The algorithm is divided into three main stages: crossover (the formation of population), selection and mutation. A GA works until the result is acceptable or the number of generations (cycles) reaches a predetermined value. In general, the use of a GA eliminates the task of exhaustive search. Therefore, a GA is widely used in solving a wide variety of tasks. In this paper, we used a simple GA. The GA parameters were chosen as follows: number of individuals – 50; number of generations – 100; mutation coefficient of 0.1; crossover coefficient of 0.5.

The parameters and voltage waveforms were calculated in TALGAT software [8]. It was assumed that a T-wave is propagating along the MF. The authors considered the losses in conductors and dielectrics. In this case, they calculated the matrices of per-unit-length resistances **R** (for the losses in the conductors) and conductance **G (**for the losses in the dielectrics). Taking into account the losses, the authors used a widely known model [9] of the frequency dependence of the relative permittivity and the tangent of the dielectric loss angle of FR-4 to calculate matrix **G**. The entries of matrix **R** were calculated with account of the skin effect, the proximity effect and losses in the ground plane by the method proposed in [10].

As an exciting pulse, let us use a digitized signal of the C9-11 oscilloscope. It was measured at 50 Ω load, with an amplitude of 0.657 V. The durations of rise, fall and the flat top were 27, 29 and 9 ps, respectively, so the overall duration was 65 ps. (Durations were measured at levels of 0.1–0.9). A schematic diagram of an MF is shown in Figure 1 and the cross-section of an MF is shown in Figure 2.

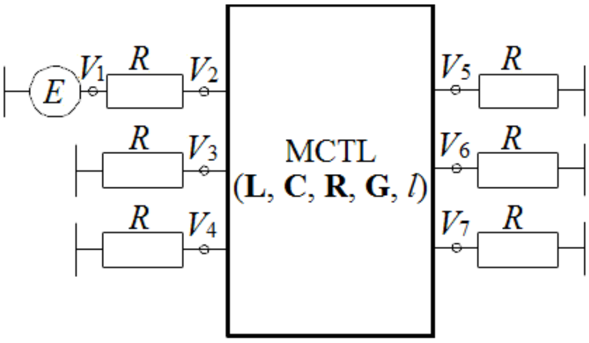


Figure 1. Schematic diagram for simulation

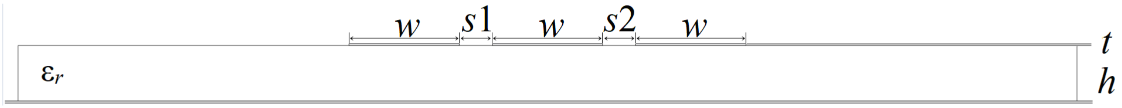
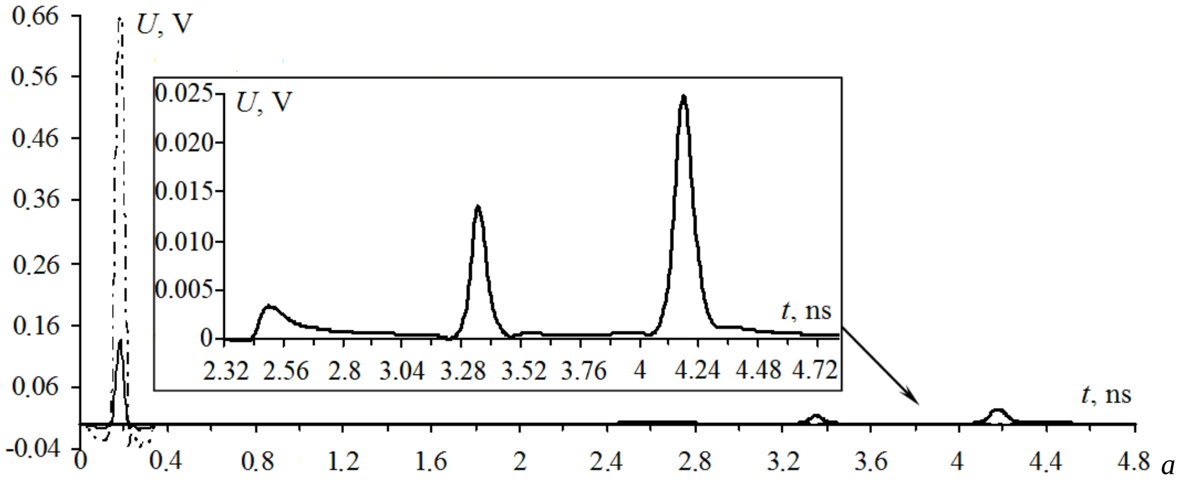


Figure 2. Cross section of a three-conductor MF

Let us suppose that for a designer, the amplitude, maximum-time, and minimum-time criteria are essential, while the time-interval criterion is less important. As a result of the GA optimization with M_1=M_2=M_3=0.3 and M_4=0.1, the authors obtained the values of *t*=176 µm, *h*=200 µm, *s*1=4 µm and *s*2=48 µm. The amplitude of the output signal was 0.0247953 V, the per-unit-length delays are equal to 3.75545, 5.26322 and 6.64469 ns/m, so the differences in the per-unit-length delays of adjacent pulses are equal to 1.50777 and 1.38147 ns/m, and their difference is 0.1263 ns/m, the difference between their maximum and minimum values is 2.88924 ns/m. The waveforms at the input and output of the MF with the parameters after the GA optimization are presented in Figure 3 (a).

Let us suppose that for a designer the time-interval, maximum-time, and minimum-time criteria are essential, while the amplitude criterion is less important. Then one can define M_1=0.1 and M_2=M_3=M_4=0.3. As a result of optimization performed with a GA, the authors obtained the values of *t*=200 µm, *h*=201 µm, *s*1=3 µm and *s*2=44 µm. The amplitude of the output signal was 0.0249575 V, the per-unit-length delays are equal to 3.63304, 5.13389 and 6.63848 ns/m, so the differences in the per-unit-length delays of adjacent pulses are equal to 1.501 and 1.505 ns/m, and their difference is 0.004 ns/m, the difference of their maximum and minimum values is 3.00546 ns/m. The waveforms at the input and output of the MF with the parameters after the GA optimization are presented in Figure 3 (b).



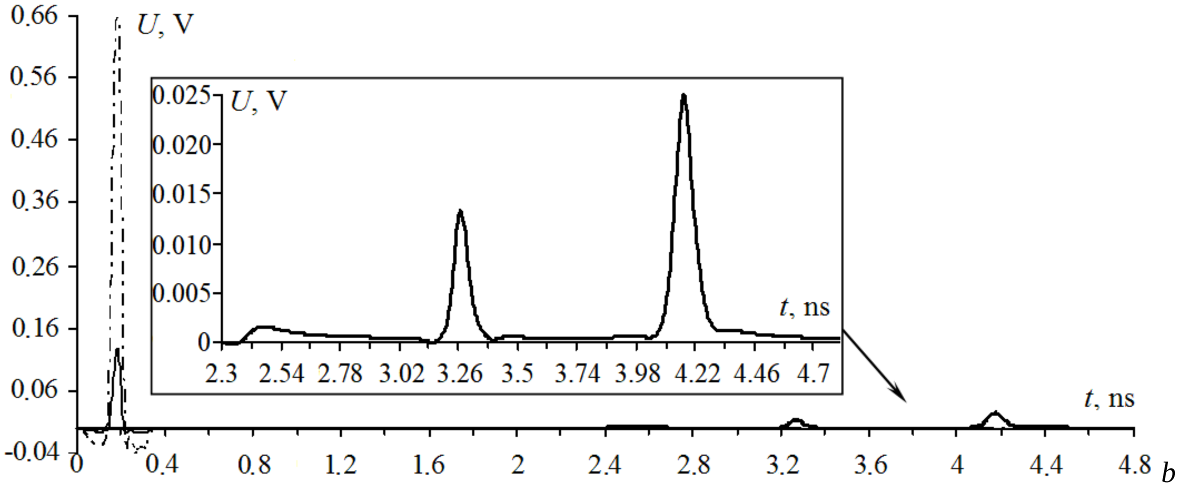


Figure 3. Waveforms at the input (–·–) and output (—) (with enlarged fragment of the signal at the output) of a three-conductor microstrip line MF after four-criteria optimization using GA with respect to the objective function (14), when the time-interval criterion is less important (a) and when the amplitude criterion is less important (b)

6. Conclusion

Thus, the paper is the first to present the results of the research into optimization of multiconductor MFs which takes into account different criteria with different weighting coefficients. In the research, the formulation of the basic (electrical) optimization criteria for an MF has been performed. The amplitude and time criteria for optimizing an MF have been derived in an analytical form, and a general multicriteria objective function has been obtained, which allows us, in the long term, to use any optimization methods and obtain higher MF characteristics. Let us note that it is useful to consider such MFs in the frequency domain, as well as their optimization using the relevant criteria.

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