Multicriteria Optimization of Four-conductor Modal Filter by Genetic Algorithms

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Abstract **– Multicriteria optimization by genetic algorithms is considered. Parameters of multiconductor modal filters (MF) are optimized. Optimization with the use of a multicriteria objective function with amplitude and time criteria for matching with the characteristic impedance of 50 Ω is considered. One amplitude, two range-time and one interval-time criteria, as well as the matching criterion are used. Thus, five-criteria optimization of five parameters of the four-conductor microstrip MF was performed. The results showed the importance of multiconductor MF optimization with simultaneous use of several criteria.**

Key words— protection device, modal filters, multicriteria optimization, genetic algorithms.

I. INTRODUCTION

Contemporary radio electronic devices have wide functional capabilities but, at the same time, they are 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]. As a result, there is a potential threat for the devices. Therefore, it is necessary to improve the protection of electronics against ultrashort pulses.

A technique of modal filtration [3] was proposed for the protection of radioelectronic devices against ultrashort pulses. This technique is based on modal decomposition of a pulse signal which occurs due to a difference between the modal delays in multiconductor transmission lines. A number of studies [4–9] on the use of multiconductor microstrip lines (MSL) as protective devices against ultrashort pulses have been performed. Results of simulation of MSL consisting of 3–5 conductors showed the decomposition of an input pulse at the end of a conductor into 3–5 pulses with the maximum amplitudes of 3, 3.6 and 4.5 times (correspondingly) less than a signal in the near end of a line [4]. Optimization showed that the equalization of the differences between delays of decomposition pulses allows increasing the duration of a pulse which is going to be completely decomposed in these structures [5]. In addition, the formulation of the main criteria for optimizing a multiconductor modal filter (MF) has been performed and an example of its optimization has been given by criteria of the minimization of the maximum output amplitude and the maximization of a difference of time delays between the first and the last decomposition pulses [6]. Experimental confirmation of the modal filtering based on multiconductor MSL was performed. For two- and three-conductor MSL, the attenuation of 11.5 and 13.7 times was obtained [7], and for four- and five-conductor – 12.6 and 15.3 times [8]. In [4–8], a heuristic search for parameters was used, but it did not provide the best results. This disadvantage is eliminated in [9] based on optimization of the three-conductor MSL MF using a genetic algorithm (GA) providing the output MF amplitude 13% less than after the heuristic search. However, in [4–9] only one criterion was used for the optimization. In [10] general objective function for the optimization by several criteria and basic optimization criteria were formulated, and four-criteria optimization of four parameters of a three-conductor microstrip MF was performed.

Meanwhile, in [10] the matching of tract is neglected. In addition, multicriteria optimization of a four-conductor microstrip MF by a genetic algorithm has not been performed before. Meanwhile, it is relevant, since the increase in the number of conductors, in general, improves the characteristics of the MF. Thus, multicriteria optimization of a four-conductor microstrip MF with the matching criterion is useful. The aim of this paper is to perform such research. To do this, first (for the sake of completeness, using the results of [10]), the formulation of the multicriteria objective function, as well as the amplitude and time optimization criteria, is presented. Then the matching criterion was proposed and formulated. Finally, the objective function for optimizing the four-conductor microstrip MF by five criteria is presented and test optimization is performed.

II. GENERAL FORMULATION OF THE MULTICRITERIA OBJECTIVE FUNCTION

Formulation of a multicriteria objective function (F) implies combining separate criteria to a single problem of minimization or maximization:

$$F \to \min \text{ or } F \to \max. \quad (1)$$

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

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$$F = \sum_i F_i \text{ or } F = \max\{F_i\} \quad (2)$$

where

$$F_i = M_i \frac{f_i}{K_i} \quad (3)$$

where f_i – objective function, K_i – normalization constant, M_i – weighting coefficient of i-th criterion, i=1, 2, …, N_C, where N_C – 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 becomes dimensionless and takes 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 in unity or as

$$M_i = \frac{1}{N_C}. \quad (4)$$

Optimization can be performed according to various criteria. Amplitude and time criteria, as well as the matching criterion are relevant for multiconductor MFs.

III. OPTIMIZATION CRITERIA

A. Amplitude Criteria

The most important criteria for optimization of MF are amplitude one. It can be considered in the time and frequency domains. It is useful to analyze the waveform $U(t)$ at the output of the MF to provide protection against the ultrashort pulse of electromotive force $E(t)$. Therefore, let us consider the amplitude criteria in the time domain. In this case, the danger is the maximum level of signal $U(t)$ at the output of the MF. Using these, we can formulate expressions for f_i and K_i:

$$f_1 = \max|U(t)|, \ K_1 = \max|E(t)|. \quad (5)$$

B. Range-time Criteria

Range-time criteria are associated with expansion of the time range of decomposition pulses at the MF output. These criteria are important for increasing the maximum duration of an exciting ultrashort pulse, which will be decomposed completely. The first one makes per-unit-length delay of the first pulse ($\tau_{\min}$) as short as possible, i.e. as determined by the light velocity in vacuum. The second one makes per-unit-length delay of the last pulse ($\tau_{\max}$) as long as possible, i.e. as determined by the light velocity in dielectric with the maximum value of the relative dielectric permittivity ($\varepsilon_{r\max}$).

1. For the first range-time criterion

$$f_2 = \tau_{\min} - \frac{1}{c}, \ K_2 = \frac{\sqrt{\varepsilon_{r\max}} - 1}{c}. \quad (6)$$

2. For the second range-time criterion

$$f_3 = \frac{\sqrt{\varepsilon_r}}{c} - \tau_{\max}, \ K_3 = \frac{\sqrt{\varepsilon_{r\max}} - 1}{c}. \quad (7)$$

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

C. Interval-time Criteria

This 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 be decomposed at the MF output completely. For arranged by increasing values of the per-unit-length delays, based on the deviation of the current values of the per-unit-length delay of the intermediate modes from the values according to uniform time intervals between the pulses, we obtain

$$f_4 = \max|\tau_i - (\tau_{\min} + (i-1)\cdot\Delta)|, \ i = 2, ..., N-1, \ K_4 = \frac{\sqrt{\varepsilon_{r\max}} - 1}{c} \quad (8)$$

where

$$\Delta = \frac{\tau_{\max} - \tau_{\min}}{N-1} \quad (9)$$

where τ_i – value of per-unit-length delay of the i-th pulse.

D. Matching criterion

One of the important criteria for MF optimizing is the matching criterion. This criterion is important for minimizing the reflection of useful high-frequency signals from the MF.

The condition for matching the two coupled lines by resistances R at their ends is defined as the geometric mean value of the impedances of the even and odd modes [11]:

$$R = \sqrt{Z_e \cdot Z_o}. \quad (10)$$

In multiconductor transmission lines, the number of propagating modes is equal to the number of conductors (N). From the eigenvalues of the impedance matrix of the line, it is possible to determine the mode impedances. The subsequent stages of determining the matching condition are apparently possible on the basis of the theory of multiconductor transmission lines, but are not clear yet for authors. Meanwhile, by analogy with a matched single transmission line, to match a multiconductor transmission line, the condition of equality of the signal amplitude at the beginning of the $U_{IN}(t)$ line and half the electromotive force of the signal source $E(t)$ can be used. Then, after simplification, we get

$$f_5 = |\max(E(t)) - 2\max(U_{IN}(t))|, \ K_5 = \max|E(t)|. \quad (11)$$

These criteria must be used for N>2. However, it requires the calculation of the response at the beginning of the line, although it does not require significant additional costs in the analysis in the frequency domain.

IV. OPTIMIZATION OF THE FOUR-CONDUCTOR MF

To test the theory, the four-conductor microstrip MF was optimized with the help of a GA. A multicriteria objective function that combines one amplitude, three time, and also the matching criterion (obtained for N=4) looks (with weight coefficients equal to 1) as

$$F=\frac{\max(U(t))}{\max(E(t))}+\frac{\tau_1-\frac{1}{c}}{\frac{\sqrt{\varepsilon_{r\max}}-1}{c}}+\frac{\frac{\sqrt{\varepsilon_{r\max}}}{c}-\tau_4}{\frac{\sqrt{\varepsilon_{r\max}}-1}{c}}+ \\ +\frac{\max\left(\left|\tau_2-\frac{\tau_4+2\tau_1}{3}\right|,\left|\tau_3-\frac{\tau_1+2\tau_4}{3}\right|\right)}{\frac{\sqrt{\varepsilon_{r\max}}-1}{c}}+ \\ +\frac{\left|\max(E(t))-2\max(U_{IN}(t))\right|}{\max\left|E(t)\right|}. \qquad (12)$$

GA is an evolutionary algorithm, with the main idea of using the ideas of evolution theory to solve optimization problems. The algorithm is divided into three main stages: crossing (the formation of the population), selection and mutation. GA works until the result is acceptable or the number of generations (cycles) reach a predetermined value. In general, the use of GA eliminates the task of exhaustive search. Therefore, GA is widely used in solving a wide variety of tasks. In this paper, we used 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.

Parameters and forms of the signal were calculated in TALGAT software [12]. It was assumed that a T-wave is propagating along the MF. Losses in conductors and dielectrics were considered. A digitized signal of the oscilloscope C9-11 was used as an exciting pulse, it was measured at 50 Ω load, with an amplitude of 0.657 V. Durations of rise – 27 ps, fall – 29 ps and flat top – 9 ps, so that the overall duration – 65 ps. (Durations were measured at levels of 0.1–0.9). Schematic diagram of the MF is shown in Fig. 1, and the cross section with parameters after optimization is shown in Fig. 2.

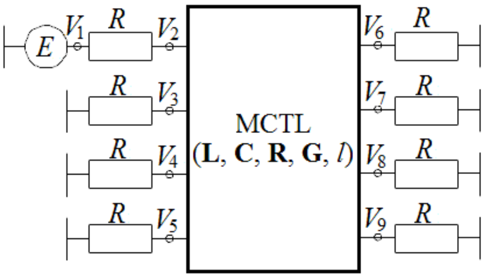

Fig. 1. Schematic diagram for simulation

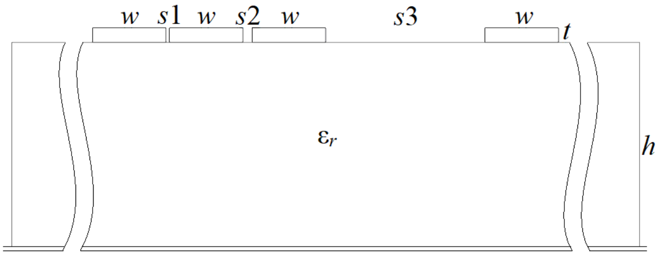

Fig. 2. Cross sections of four-conductor MF

MF was optimized for the following parameters: width of conductors (*w*) is 180 µm, relative permittivity (ε_r) is 5, length of line (*l*) is 60 cm, *R*=50 Ω. The value of *w* was unchanged, as well as the value of ε_r. The thickness of conductors *t*, thickness of dielectric *h* and values of conductors separations *s*1, *s*2 and *s*3 were optimized for the five-criteria objective function (12). Optimization of *t* was performed in a range of 10–200 µm, *h* – in a range of 200–2000 µm, and *s*1, *s*2 and *s*3 – 1–1000 µm. As a result of the optimization with the help of GA, the values of *t*=35 µm, *h*=501 µm, *s*1=8 µm, *s*3=23 µm and *s*3=390 µm were obtained. The amplitude of the signal at the output of the line was 0.0188094 V. The per-unit-length delays are equal to 4.57947, 5.10955, 5.63149 and 6.15283 ns/m, so that the differences in the per-unit-length delays of adjacent pulses are equal to 0.53008, 0.52194 and 0.52134 ns/m, i.e. coincide up to 0.01 ns/m, differing by 2%. Meanwhile, the amplitude at the input of the MF was 0.323928 V, which is 2.03 times less than the electromotive force of the source (0.657608 V), thereby ensuring the matching. The waveforms at the input and output of the four-conductor MF with parameters after the optimization using GA are presented in Fig. 3.

V. CONCLUSION

A matching criterion is proposed and formulated for optimizing a multiconductor MF. A five-criterion objective function for a four-conductor microstrip MF is obtained. The optimization of five parameters of a four-conductor microstrip MF was performed on five criteria. At the output of the MF, well matched to the 50 Ω path, a signal with an amplitude of 0.0188094 V and close differences in the per-unit-length delays of adjacent pulses was obtained. Thus, the attenuation factor of 34.9 times is possible not only for ultrashort pulse with the duration of 65 ps, but also much larger (about 100–200 ps).

In [10], a three-conductor MF was obtained for *s*1=10 µm and *s*2=115 µm with a maximum amplitude at the output of 0.0306662 V. The optimization was carried out according to four criteria and four parameters in the same range. The amplitude at the output of the MF of this work is 63% less than in [10].

In conclusion, we note the methodological significance of the obtained results:

1. A very general five-criterion objective function, suitable for optimizing any four-conductor MF.

2. The interval-time criterion for a four-conductor MF is obtained in an analytical form.

3. Equalizing time intervals between the decomposed pulses is approved.

These results can be successfully applied to optimize one of the new and advancing version of a four-conductor MF, called a mirror-symmetric MF [13]. In the MF, the equality of the pulse amplitudes is relatively easy to obtain, while equalizing the intervals between pulses may require optimization.

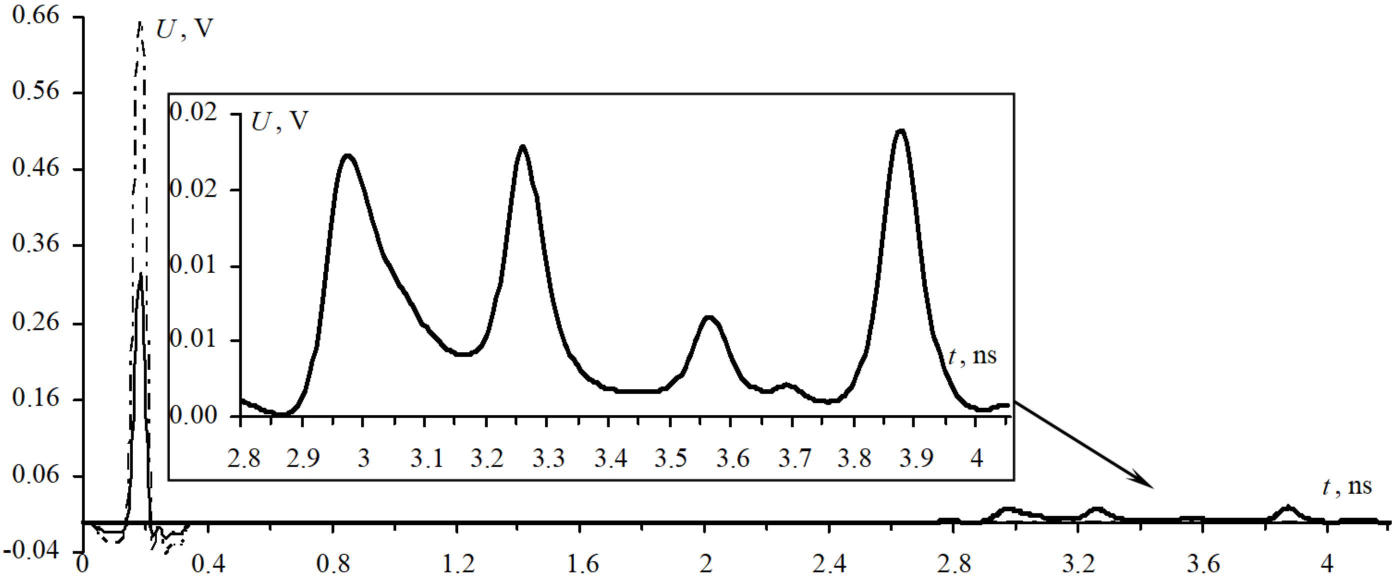

Fig. 3. Waveforms of the electromotive force (–·–·–), at the input (——) and output (——) (with enlarged fragment of the signal at the output) of four-conductor microstrip line MF with the parameters obtained as a result of five-criteria optimization of five parameters using GA

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