Modal Filters Based on a Microstrip Line with Overhead Conductors Grounded at Both Ends

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***Abstract*—The paper describes two new modal filters (MF) which represent a conventional microstrip line (MSL) with one or two overhead conductors which are grounded at both ends of the MSL. The cross-sections of the line at certain parameter values were built in the TALGAT system. The matrices of per-unit-length coefficients of electromagnetic and electrostatic induction of lines were calculated, as well as the per-unit-length delays, eigenvectors of voltage, and the time response to the excitation of an ultrashort pulse. The pulse was attenuated by more than 2 times. The difference in the characteristics of the new MFs from the known ones is the following: the voltage amplitudes of the first two pulses are equal both when the passive conductor is short-circuited at both ends of the reference conductor and when there is a sharp asymmetry in the arrangement of the active and passive conductors relative to the reference one. The time responses revealed additional pulses with delays equal to linear combinations of mode pulse delays. For the validity of the results obtained, the computations were evaluated by comparing the results obtained by the numerical method and the analytical model.**

Keywords — microstrip line, modal filter, per-unit-length delay, time response, ultrashort pulse, analytical model.

I. Introduction

Microstrip lines (MSL) are massively used to transmit electrical signals and power to various elements of electrical circuits. Therefore, they are constantly being modified to improve their capabilities [1]. The most famous is the conventional MSL consisting of a reference conductor in the form of a conducting layer, a dielectric substrate on the reference conductor, and a signal conductor in the form of a strip on the substrate [2]. The disadvantage of such MSL configuration is that it does not provide protection against ultrashort pulses (USP). Meanwhile, an ordinary MSL with certain values of parameters and modifications can have the properties of a modal filter (MF) [3, 4], and the resulting devices could be patentable [5, 6]. The purpose of this work is to present generalized and more detailed results of the study of two new MFs.

II. Structures and Diagrams

We propose two modifications of the MSL differing in the presence of one or two symmetrical conductors mounted above the MSLs and connected at the ends of the MSL with a reference conductor (Fig. 1). Cross-section parameters are the following: t=18 μm, $w1$=1 mm, h=1 mm are for both modifications; w=0.9 mm, $h1$=0.2 mm are for the MSL with one overhead conductor (Fig. 1 *a*); w=0.3 mm, $h1$=0.1 mm, s=0.45 mm are for the MSL with two symmetrical surface-mounted conductors (Fig. 1 *b*). Such designs make it possible to decompose the USP exciting between the signal and reference conductors of the MSL into 2 pulses of equal amplitudes. The result is the possibility of protection against USPs through its modal decomposition.

The possibility of USP decomposition is shown by simulating the structures whose cross–sections are shown in Fig. 1, circuit diagrams – in Fig.2, USP exciting – in Fig. 3. The circuit parameters are the following the line length l=1 m, the internal resistances of the USP source and the load $R1$=$R2$=50 Ω. The USP source has an electromotive force amplitude of 5 V, and the rise, flat top and fall times are 50 ps each. Losses in conductors and dielectrics were not taken into account.

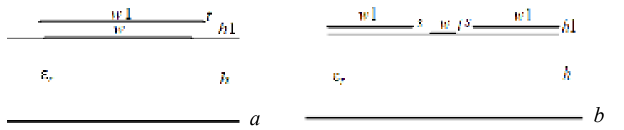

Fig. 1. The cross-sections of the proposed MFs with one (*a*) and two (*b*) overhead grounded conductors

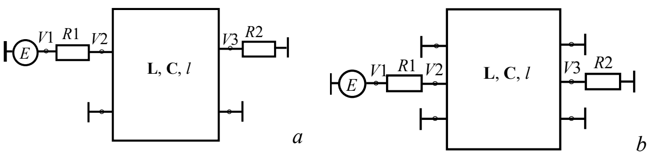

Fig. 2. The simulated circuit diagrams for MSLs from Fig. 1 *a* (*a*) and Fig. 1 *b* (*b*)

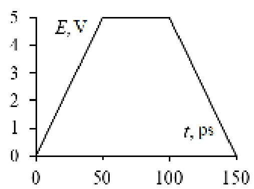

Fig. 3. The USP source electromotive force waveform

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III. Simulation Results

The set of cross-sectional parameters determines the matrices of per-unit-length coefficients of electromagnetic (**L**) and electrostatic (**C**) induction of lines. Matrices **L** and **C** were calculated in the TALGAT software for the lines from Fig. 1:

$$\mathbf{L}=\begin{bmatrix} 426.91 & 344.02 \\ 344.02 & 444.54 \end{bmatrix} \text{nHn/m},$$

$$\mathbf{C}=\begin{bmatrix} 123.69 & -55.83 \\ -55.83 & 69.64 \end{bmatrix} \text{pF/m}.$$

$$\mathbf{L}=\begin{bmatrix} 518.1 & 235.8 & 235.8 \\ 235.8 & 412.7 & 147.8 \\ 235.8 & 147.7 & 412.7 \end{bmatrix} \text{nHn/m}, \tag{1}$$

$$\mathbf{C}=\begin{bmatrix} 72.82 & -22.06 & -22.06 \\ -22.06 & 60.61 & -5.667 \\ -22.06 & -5.667 & 60.61 \end{bmatrix} \text{pF/m}.$$

The square root of the eigenvalues of the product of these matrices determines the values of the per-unit-length delays (τ) of the modes propagating in the lines. For Fig. 1 *a* $\tau 1$=3.41 ns/m, $\tau 2$ =5.81 ns/m, and for Fig. 1 *b* $\tau 1$=4.32 ns/m, $\tau 2$=5.38 ns/m, $\tau 3$=4.19 ns/m. Each of them corresponds to an eigenvector of the voltage:

$$\mathbf{u1}=\begin{pmatrix} 0 \\ 0.9 \end{pmatrix},\ \mathbf{u2}=\begin{pmatrix} 0.8 \\ 0.6 \end{pmatrix}; \tag{2}$$

$$\mathbf{u1}=\begin{pmatrix} 0.7 \\ -0.2 \\ 0.7 \end{pmatrix},\ \mathbf{u2}=\begin{pmatrix} -0.4 \\ -0.8 \\ -0.4 \end{pmatrix},\ \mathbf{u3}=\begin{pmatrix} -0.7 \\ 0 \\ 0.7 \end{pmatrix}. \tag{3}$$

The validity of the results is confirmed by their comparison to the vectors presented in [7] in the form (4) for example for a 3-conductor line:

$$\mathbf{u1}=\begin{pmatrix} a \\ 1 \\ a \end{pmatrix},\ \mathbf{u2}=\begin{pmatrix} -b \\ 1 \\ -b \end{pmatrix},\ \mathbf{u3}=\begin{pmatrix} -1 \\ 0 \\ 1 \end{pmatrix}. \tag{4}$$

For the line in Fig. 1 *a*, the time interval between the first two decomposition pulses (about 2.4 ns) is determined by the product of the line length (1 m) and the difference in per-unit-length delays of modes 1 and 2 (about 2.4 ns/m). This is confirmed by the calculated voltage waveforms at the beginning (*V*2) and the end (*V*3) of the signal conductor shown in Fig. 4 *a*. One can see, at node 2 there are pulses with an interval of about 2.4 ns between them and equal amplitudes of about 1.2 V.

For the line in Fig. 1 *b* due to the symmetry of the two overhead conductors, the amplitude of the pulse of mode 3 is zero, and there remain only pulses of modes 1 and 2. The interval between them (about 1 ns) is determined in the same way: 1m*(5.38–4.32) ns/m. Two pulses with equal amplitudes of about 1.2 V arrive to the line end (Fig. 4 *b*).

Thus, both lines show the possibility of attenuating (by a factor of 2 in relation to half of the EMF) the exciting USP (with a total duration less than specified intervals), and hence, protecting the circuit from it.

It is noteworthy that the first design is simpler (1 conductor on top, not 2; the air gap is larger), but allows decomposing a USP which is 2.4 times longer.

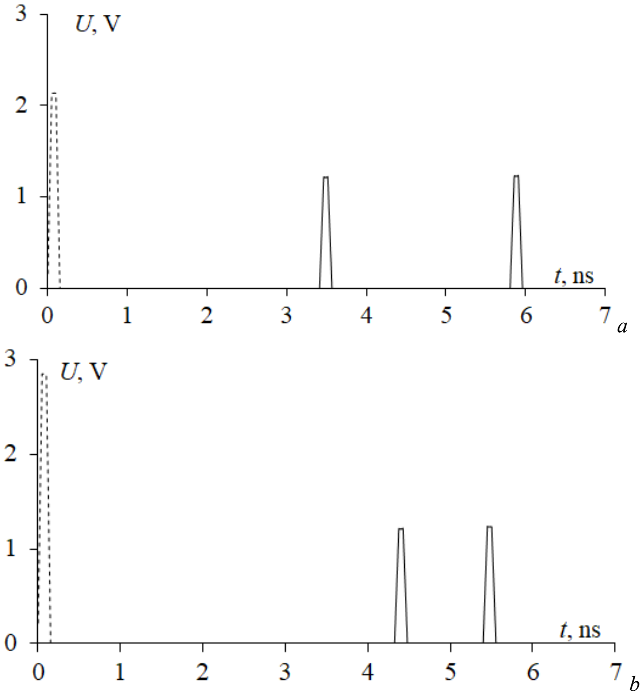

Fig. 4 The voltage waveforms at the beginning (--) and the end (-) of the MF in Fig. 1 *a* (*a*) and Fig. 1 *b* (*b*)

Meanwhile, time responses which take into account subsequent reflections are indicative (Fig. 5). In particular, in addition to pulses with delays multiple of delays of mode pulses, additional pulses appear with delays proportional to their combinations. These pulses arrive at the input and have positive polarity, and at the output – negative polarity.

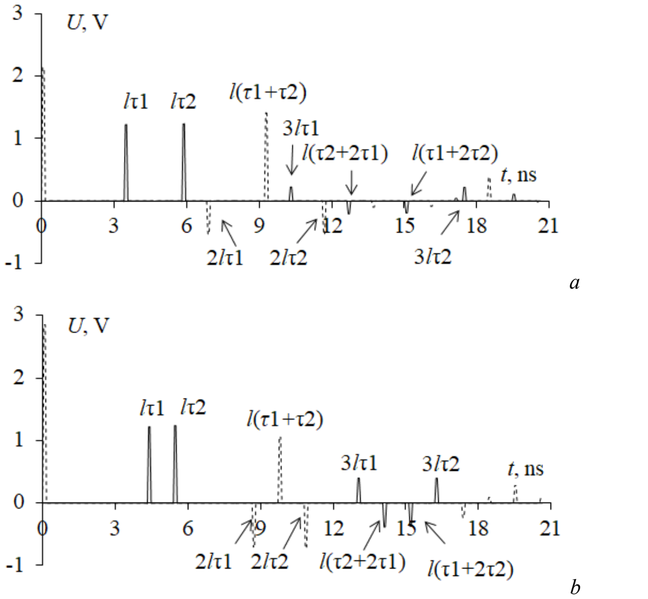

Fig. 5. The voltage waveforms at the beginning (- -) and the end (-) of the MFs in Fig. 1 *a* (*a*) and Fig. 1 *b* (*b*) which take into account reflections

IV. Analytical Model

To check the results, it is useful to compare them with the results obtained by other approaches. Therefore, we derived an analytical model that is suitable for calculating the response of the MF with one grounded overhead conductor and made a corresponding comparison.

The analytical approach is known to be based on the application of the method of modal decomposition in the time domain [7-9]. It was used to obtain the analytical mathematical model of the time response of the MF to the impulse excitation for the special case when the passive conductor is short-circuited to the circuit ground at the ends. Let us briefly introduce it.

The model uses:

– matrices $\mathbf{T}_V$ and $\mathbf{T}_I$, calculated from eigenvectors of matrices **LC** and **CL**

$$\mathbf{T}_V = \begin{bmatrix} T_{Vc,1} & T_{Vd,1} \\ T_{Vc,2} & T_{Vd,2} \end{bmatrix},\ \mathbf{T}_I = \begin{bmatrix} T_{Ic,1} & T_{Id,1} \\ T_{Ic,2} & T_{Id,2} \end{bmatrix}; \tag{5}$$

– modal impedance matrix

$$\mathbf{R}_m = \frac{R}{(T_{Vc,1}T_{Vd,2} - T_{Vc,2}T_{Vd,1})} \begin{bmatrix} T_{Vd,2}T_{Ic,1} & T_{Vd,2}T_{Id,1} \\ -T_{Vc,2}T_{Ic,1} & -T_{Vc,2}T_{Id,1} \end{bmatrix}; \tag{6}$$

– reflection coefficients

$$\begin{aligned} \mathbf{\Gamma}_m &= (\mathbf{R}_m \mathbf{Z}_{cm}^{-1} + \mathbf{E})^{-1} (\mathbf{R}_m \mathbf{Z}_{cm}^{-1} - \mathbf{E}) \\ &= \begin{bmatrix} \Gamma_{cc} & \Gamma_{cd} \\ \Gamma_{dc} & \Gamma_{dd} \end{bmatrix} \end{aligned} \tag{7}$$

where **E** is the unit matrix and $\mathbf{Z}_{cm}$ is the matrix of characteristic mode impedances

$$\mathbf{Z}_{cm} = \begin{bmatrix} \sqrt{\dfrac{L_{mc}}{C_{mc}}} & 0 \\ 0 & \sqrt{\dfrac{L_{md}}{C_{md}}} \end{bmatrix} \tag{8}$$

where L_{mc} and C_{md} are elements of diagonalized matrices **L** and **C**;

On the basis of (5) – (8), the analytical model of the time response at the output of the MF was obtained:

$$\begin{aligned} V(t) &= T_{Vc,1}\left[(1+\Gamma_{cc})V_{0c}(t-T_c) + \Gamma_{cd}V_{0d}(t-T_d)\right] \\ &+ T_{Vd,1}\left[(1+\Gamma_{dd})V_{0d}(t-T_d) + \Gamma_{dc}V_{0c}(t-T_c)\right] \end{aligned} \tag{9}$$

where T_c, T_d are common mode and differential mode delay times, V_{0c}, V_{0d} are the source vectors of the initially incident common and differential modes defined as

$$\mathbf{V}_{0m}(t) = (\mathbf{E} + \mathbf{R}_m \mathbf{Z}_{cm}^{-1})^{-1} \mathbf{V}_m(t) = \begin{bmatrix} V_{0c}(t) \\ V_{0d}(t) \end{bmatrix} \tag{10}$$

where $\mathbf{V}_m(t)$ is the matrix of modal sources

$$\mathbf{V}_m(t) = \mathbf{T}_V^{-1}\mathbf{V}(t) = \begin{bmatrix} V_c(t) \\ V_d(t) \end{bmatrix} \tag{11}$$

where $\mathbf{V}(t)$ is matrix of voltage sources

$$\mathbf{V}(t) = \begin{bmatrix} V_{in}(t) \\ 0 \end{bmatrix} \tag{12}$$

where $V_{in}(t)$ is the electromotive force of an exciting source.

For the given values of the MF parameters, the model for calculating the response at the output of the active line is

$$\begin{aligned} V_a(l,t) &= 0.778\left[0.576V_{0c}(t-T_c) - 0.905V_{0d}(t-T_d)\right] \\ &-0.005\left[0.569V_{0d}(t-T_d) - 0.362V_{0c}(t-T_c)\right]. \end{aligned} \tag{13}$$

The results obtained earlier by the numerical method and analytically according to (13) are shown in Fig. 6, and the amplitudes and delays of pulses at the MF output are summarized in Table I.

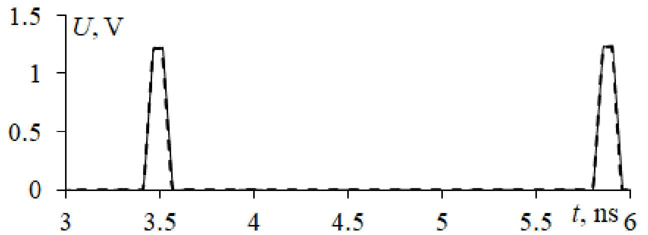

Fig. 6. Voltage waveforms at the output of the MF with a grounded overhead conductor, calculated by a numerical (—) method and an analytical model (– –)

TABLE I. The Amplitudes (U_1, U_2) And Delays (t_1, t_2) of Pulses at the Output of the MF with a Passive Overhead Conductor, Calculated by the Numerical Method and the Analytical Model

Parameters	Numerical method	Analytical model
U_1, U_2, V	1.21	1.21
t_1, ns/m	3.414	3.414
t_2, ns/m	5.805	5.805

As can be seen from Fig. 6 and Table I the forms of the pulse voltages coincide in delay, amplitude, and polarity. Thus, the reliability of the results obtained for this MF is confirmed by the analytical model.

V. Conclusion

In conclusion, let us note the differences between the proposed MF designs and the known ones presented in the monograph [10]:

1. The minimum and equal pulse voltages at the output of the known MFs, as a rule, were obtained when resistances at the ends of the passive conductor are equal to the geometric mean of the wave impedances of the modes and in some MFs – with a short circuit at one end and an open circuit at the other. But in the proposed MFs, the equal pulse voltages are obtained when the passive conductor is short-circuited to the reference one at both ends.

2. Many well-known MFs have a symmetrical (or close to it) arrangement of active and passive conductors relative to the reference one, which ensures equal amplitudes of the pulse voltage. But in the proposed MFs, this is ensured with a sharply asymmetric arrangement of these conductors relative to the reference one.

3. Among the subsequent pulses, there are additional pulses with delays equal to linear combinations of the mode pulses.

4. In the MF of Fig. 1 *b*, attention is drawn to the fact that passive conductors short-circuited to a reference one

can be interpreted as a reference conductor divided into several conductors connected at the ends.

5. The subsequent pulses coming to the end of the line are multipolar, and their amplitudes are close.

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