Delay Line Protecting against Ultrashort Pulses with Increased Duration

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***Abstract* – The paper shows the possibility to increase the duration of ultrashort pulse which can be decomposed in the one turn meander delay lines. For this purpose, we suggested a condition that increases duration of ultrashort pulse up to a value that is equal to twice the product of the minimum of per-unit-length delays of even and odd modes of a signal and the length of half-turns. Simulation showed the expansion of ultrashort pulses with increased duration when this condition is fulfilled. It has been revealed that such decomposition without proper optimization results in the increased amplitude of the output signal. Therefore, an additional optimization was made to provide additional reduction of the amplitude of ultrashort pulse resulting in 32% of input signal.**

***Index Terms* – Ultrashort pulse, even and odd modes, meander line, optimization**

I. Introduction

NOWADAYS, the task of electronic equipment (EE) protection against intentional electromagnetic interference (IEMI) is very important. Currently, there are registered many cases of implementation of the powerful electromagnetic pulse generators by malefactors for disabling telecommunication and safety systems of the important objects of society infrastructure (telephone stations, banks etc.) [1]. Particularly, the IEMI problem is considered as evident threat for the critical systems such as infrastructure of fuel and energy complex. The first discussion of IEMI problem began from the professor V. Lobarev's plenary lecture at the AMEREM conference in 1996 [2]. Nowadays, the IEMI problem is an abiding theme of discussions, for example, at the AMEREM/EUROEM/ASIAEM conferences. Also, a number of major international projects, such as HIPOW (Protection of Critical Infrastructures against High Power Microwave Threats), STRUCTURES (Strategies for The impRovement of critical infrastrUCTUre Resilience to Electromagnetic attackS), SECRET (SECurity of Railways against Electromagnetic aTtacks), are aimed at EE protection against IEMI [3–5].

Nanosecond and subnanosecond pulses are one of the most dangerous types of IEMI because such ultrashort pulses are able to penetrate into EE bypassing electromagnetic shields and due to high power can cause malfunction of the sensitive circuits. Traditionally, for protection against ultrashort pulses, such devices as various LCR-filters, dischargers and noise limiters are connected to the input of EE. But these devices have a number of deficiencies, the most crucial of them are low power, insufficient response speed and stray parameters. These deficiencies leads to insufficient protection against high-power ultrashort pulses, thus complex multistage devices are required for construction of the proper protection in a wide range of effects. Meanwhile, simple and cheap devices are required in real practice. Thus the investigation of the new ways of protection and construction of the devices based on them are important.

In that context, it is worth to note the proposed simple approach to the protection of EE, which is based on the use of distortion in a simple printed structure being one turn of a meander delay line [6–8]. The advantage of the approach is that its implementation does not require the protection device itself. Widely spread PCB elements - meander delay lines - are thought to be promising for this aim. Protection against ultrashort pulses with this approach provides attenuation of its amplitude due to the signal decomposition into a sequence of pulses with lower (relatively to the original) amplitude. To do this, we should provide some conditions that relate geometric and electrical parameters of a line with signal parameters. These conditions may be changed depending on the type of dielectric filling. For example, for the line with a homogeneous dielectric filling, the pulse of the main signal should come after near-end crosstalk (in coupling lines terminology) and it can be achieved if the delay in the line (the product of twice per-unit-length delay and halve turn length) is more than the signal duration [9]. After that, optimization of coupling between the signal conductors of the line minimizes and equalizes amplitudes of the crosstalk and the main pulse at the end of the line [6]. As per-unit-length delays of modes are not equal in the line with the inhomogeneous dielectric filling, it is necessary to execute the condition for the arrival of the main signal to the end of line after the finishing of near-end crosstalk pulse

$$2\cdot\tau_{min}\cdot l > t_r + t_d + t_f, \quad (1)$$

where τ_{min} is the minimum value of per-unit-length delays of even and odd modes of the line and t_r, t_d and t_f are rise time, flat top and fall of a pulse, correspondingly.

The difference of per-unit-length delays can also provide additional attenuation due to the main signal decomposition into two pulses of even and odd modes [7]. This decomposition is ensured by the condition

$$2\cdot(\tau_{max}-\tau_{min})\cdot l > t_r + t_d + t_f, \quad (2)$$

where τ_{max} is the maximum value of per-unit-length delays of even and odd modes of the line. Mentioned possibility of the EE protection against ultrashort pulses based on the turn of meander line has been experimentally proved by the example of a microstrip line, which showed that ultrashort pulse was attenuated by factor of 6.3 [10].

It is interesting to note that the left-hand side of the inequality (2) limits the maximum duration of decomposed pulse. For the duration of ultrashort pulse being much less than the left-hand side of (2), its decomposition into three main pulses will be observed (pulse of crosstalk, pulses of even and odd modes). But for the duration of ultrashort pulse being a bit more than the left-hand side of inequality, waveforms of the even and odd modes pulses overlay and the signal amplitude at the end of the line is equal to the sum of this pulses. Thus, the ultrashort pulse amplitude with increased duration will not be attenuated at the end of a turn. However, for the effective protection of the EE, it is important not only to reduce the amplitude of the ultrashort pulse but also to increase the duration of fully decomposed ultrashort pulse. Therefore, the aim of this paper is to investigate the possibility of increasing of the ultrashort pulse duration, which may be decomposed in the one turn of a meander line. For this purpose, first of all, we need to demonstrate the case, where the increasing of the ultrashort pulse duration leads to the increasing of the output signal amplitude. The line from paper [7] seems to be suitable for this. After that, we need to propose the approach to the extension of a working range of the effects and to show the implementation of this approach via simulation.

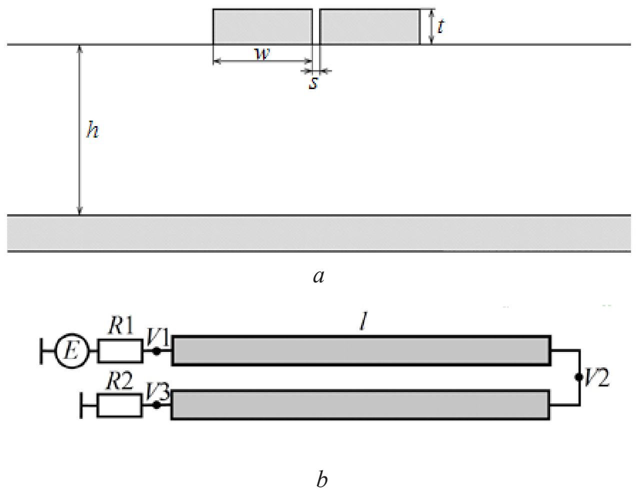


Fig. 1. Cross section (*a*) and scheme (*b*) of the meander microstrip line

II. Initial Data for Simulation

First of all, let us consider the case from paper [7]. Fig. 1 presents cross section and circuit diagram of the line. Initially, parameters of the cross section in Fig. 1*a* were chosen as follows: width and thickness of the signal conductor w=300 μm and t=105 μm, accordingly, distance between conductors s=23 μm, thickness of the dielectric substrate h=510 μm, substrate permittivity ε_r=10.

Fig. 1*b* shows a diagram of the line connections. It consists of two parallel conductors, interconnected at the one end. One of the conductors is connected to a pulse source, which is presented by e.m.f. source E and internal resistance $R1$. Another conductor is connected to the receiving unit, which is shown as $R2$. In order to minimize reflections at the input and output of the line, $R1$ and $R2$ are taken to be equal to the geometric mean of the impedance of even and odd modes of a line. Two trapezoidal pulses with amplitude of 1 V and duration of 200 and 500 ps (duration of the rise and fall of 50 ps, and the flat top duration of 100 ps and 400, respectively) are selected as the exciting pulses. Let us note, that, at first, line length l=45 mm is assigned to fulfill the conditions (1) and (2) with a pulse duration of 200 ps.

III. Simulation Results and Discussion

Below are the matrixes **C** and **L** for the structure in Fig. 1*a*, obtained by method of moments [11]:

$$\mathbf{C} = \begin{bmatrix} 232.06 & -138.12 \\ -138.12 & 232.06 \end{bmatrix} \text{pF/m},$$

$$\mathbf{L} = \begin{bmatrix} 390.34 & 309.03 \\ 309.03 & 390.34 \end{bmatrix} \text{nH/m}.$$

Simulation of the waveform at the end of a meander line turn with excitation pulses of 200 and 500 ps is given in Fig. 2.

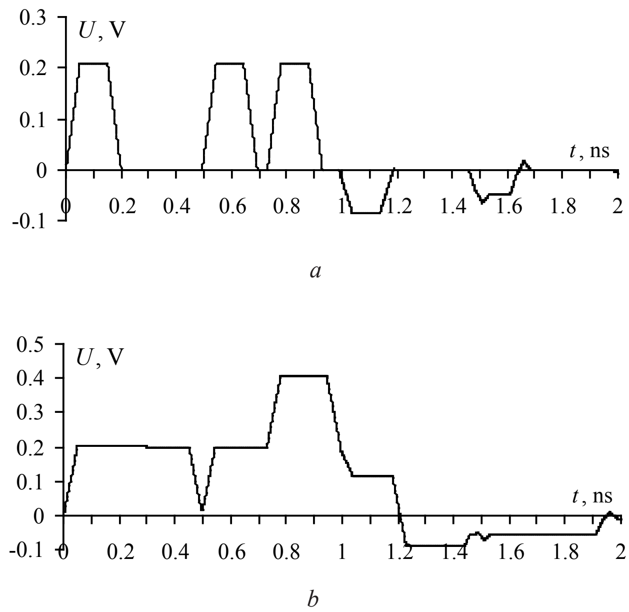


Fig. 2 Waveforms at the end of investigated line with the excitation pulses duration of 200 (*a*) and 500 ps (*b*)

As seen from Fig. 2*a*, qualitative estimations given above are proved by quantitative estimations obtained as a result of simulation. Ultrashort pulse with duration of 200 ps is decomposed at the end of a meander line into a sequence of three pulses. The amplitude of pulses is equal to 40% of the signal level at the beginning of the line. But the situation changes if the excitation pulse duration increases up to 500 ps. So, the signal at the end of the line is already presented as a sequence of two pulses, where the first is still a near-end crosstalk from the signal front and the second pulse is obtained as a result of superposition of even and odd mode pulses. It leads to increasing of the signal amplitude at the end of the line up to 80% of the signal level at the beginning of the line. Thus, the assigned parameters of the meander line turn do not provide the protection against ultrashort pulses with duration of more than 200 ps.

It is remarkable, that optimization of the parameters of cross-section of a meander line turn can help to obtain the ultrashort pulse decomposition maximizing the duration of the pulse. It is obvious, that this condition is an equalization of the minimum delay and the difference of the maximum and the minimum delays, that is equivalent to equating of the left sides of (1) and (2), which gives

$$\frac{\tau_{max}}{\tau_{min}} = 2. \quad (3)$$

Using

$$\tau = \frac{\sqrt{\varepsilon_{re}}}{c},$$

where ε_{re} is effective dielectric constant and c is speed of light, we get

$$\frac{\varepsilon_{remax}}{\varepsilon_{remin}} = 4.$$

Then, for a structure that ensures one of the most extreme cases, the propagation of one of the modes in the air (ε_{remin}=1), we obtain ε_{remax}=4, which possible only with ε_r>4 in case of one dielectric.

The condition (3) does not remove the restrictions of the ultrashort pulse duration, which are imposed by a right-hand side of condition (2). But its fulfillment allows the increasing of this duration up to the product of doubled length of a halve turn and the minimum value of per-unit-length delays of even and odd modes. This condition allows spreading the even and odd modes pulses to specified tame value for fixed line length. Simulation and optimization of the line cross section parameters from Fig. 1*a* are executed to demonstrate it. As a result, the cross section parameters are chosen to ensure the conditions (1), (2) and (3): *w*=300 μm, *t*=205 μm, *s*=17 μm, *d*=900 μm, *h*=510 μm, ε_r=30. Computated of matrices **C** and **L**:

$$\mathbf{C} = \begin{bmatrix} 662.2 & -401.7 \\ -401.7 & 662.2 \end{bmatrix} \text{pF/m}, \ \mathbf{L} = \begin{bmatrix} 352.7 & 312.1 \\ 312.1 & 352.7 \end{bmatrix} \text{nH/m}.$$

Similar to the previous case, simulation of the waveforms at the end of a meander line turn, excited by pulses of 200 and 500 ps, was carried out (Fig. 3).

Fig. 3 shows that the condition (3), in contrast to previous studies, provides decomposition of pulses with durations of 200 and 500 ps in the turn of meander line into three main

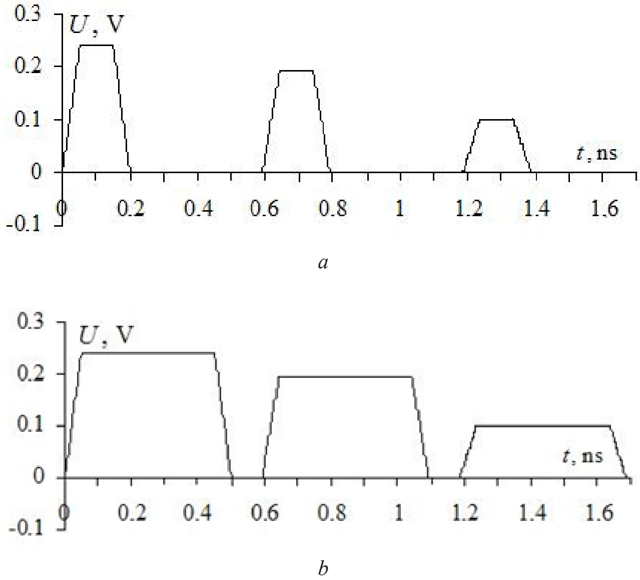


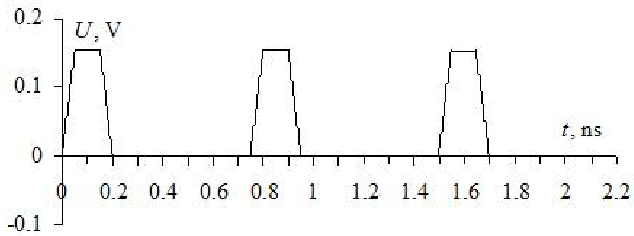
Fig 3 Waveforms at the end of investigated line with the excitation pulses duration of 200 (a) and 500 ps (b) and fulfilled condition (3)

pulses. In both cases their propagation through turn of a meander line leads to the decomposition of the signal into three main pulses, however, these pulses are of different amplitude. The maximum amplitude of the output signal is about 50% of the amplitude of the signal at the beginning of the line regardless of duration of the exciting pulse. Thus the meander line provides decomposition of pulses with longer duration but does not provide a proper attenuation of the ultrashort pulse amplitude. Therefore for minimization of amplitude at the output of meander line turn, we performed additional optimization of cross-section parameters (Fig. 1*a*) and resistances *R*1 and *R*2 in the diagram Fig. 1*b.* Optimal choice simultaneously provided conditions (1), (2) and (3) and the minimum amplitude of the output signal. Cross-section parameters are chosen as follows: *w*=850 μm, *t*=452 μm, *s*=46 μm, h_C=540 μm, *d*=2550 μm, ε_{rC}=40. Computated of matrices **C** and **L**:

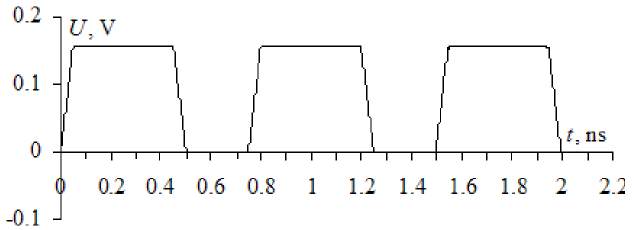
$$\mathbf{C} = \begin{bmatrix} 1100.4 & -696.8 \\ -696.8 & 1100.4 \end{bmatrix} \text{pF/m}, \ \mathbf{L} = \begin{bmatrix} 219.1 & 172.9 \\ 172.9 & 219.1 \end{bmatrix} \text{nH/m}.$$

Waveforms obtained under exciting to pulses with durations of 200 and 500 ps are shown in Fig. 4.

As can be seen from Fig. 4, additional optimization leads to equalization of the amplitudes of the first three pulses regardless of exciting pulse duration. The maximum output signal amplitude is 32% of the signal amplitude at the beginning of the line. Thus the condition (3) and additional optimization allows decomposition of an ultrashort pulse in the turn of meander line not only with increased duration but with additional attenuation. It should be noted that a further increase of the duration between the pulses of the even and odd modes is inappropriate, as it does not affect the spacing between the cross talk pulse from the front and the pulse of the fastest mode. Meanwhile, the condition (3) is useful for protection devices based on meander lines consisting of two or more turns. In such devices, each of the three main pulses (with their proper durations and delays) for the second turn (if we consider the line of the two turns) may be a separate ultrashort pulse, which can also be decomposed, that will significantly increase the attenuation of ultrashort pulse at the output of a line. It is a task for future research to carry out simulation and implementation of the devices described above.



a



b

Fig. 4 Waveforms at the output of investigated line with the duration of impact pulses 200 (a) and 500 ps (b), fulfilled condition (3) and the additional optimization

IV. Conclusions

The paper shows that it is possible to increase the duration of ultrashort pulse which can be decomposed in the one turn of meander delay line. For this purpose, we propose a condition providing an increase in the duration of ultrashort pulse to a value equal to twice the product of the minimum delay of even and odd modes of a signal and the length of line. Simulation showed decomposition of ultrashort pulses with different duration when this condition is fulfilled. However, this decompositions without proper optimization increases the amplitude of the output signal. Therefore additional optimization is made for further reduction of the amplitude of ultrashort pulse resulting in 32% of input signal.

Despite the achieved positive results, this paper used manual optimization (parameters search), which is a drawback, as it does not allow to find the most optimal parameters. Therefore, in future research it is necessary to perform automatic optimization of turn parameters, for example, using genetic algorithms.

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