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Modal Filter with Interdigital Structure of Conductors for 100 Mbit/s Ethernet Equipment Protection

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Abstract – **Protection of modern electronic equipment from electromagnetic interference is an important issue. Protection against ultrashort pulses is possible using the modal decomposition. The advantages and disadvantages of modal filters are described. To reduce their size, it has been proposed to use structures with a periodic profile of the conductor coupling region. Using the interdigital topology, one can change the time of arrival of the differential mode pulse, thereby controlling the difference in mode delays. Layouts of modal filters with an interdigital structure of conductors are presented. They are single-stage resistive and three-stage non-resistive Electrodynamic modeling has shown that the proposed structures effectively attenuate the ultrashort pulse and have the required bandwidth. At the same time, the dimensions of modal filters with an interdigitated structure of conductors for protecting equipment of Ethernet 100 Mbit/s are 2.7 times smaller than previously known ones.**

Keywords— modal filter, ultrashort pulse, electromagnetic interference.

I. Introduction

Protection of modern computer networks from electromagnetic interference is an important issue. Much attention is paid to the susceptibility to the effects of powerful ultrashort pulses (USP) - nanosecond and subnanosecond pulses. [1]. The use of known protection devices [2] for solving this problem is complicated by a number of conflicting requirements, for example, low mass and high reliability. In addition, USPs are able to penetrate various pieces of equipment, bypassing the instrument screens. The possibility of protection using modal filtering devices is known [3].

The physical principle of such protection is based on the effect of the decomposition of an interfering pulse in a segment of a coupled line into modes, each of which propagates with its own delay. With a non-uniform dielectric filling in the cross section of a connected line segment, the difference between these delays may be greater than the duration of the interfering pulse, and then one pulse applied between the active and reference conductors at the beginning of the segment will decompose into two pulses at the end of the segment. However, modal filters (MFs) have a number of disadvantages. One of the disadvantages are sizes. Thus, the known symmetrical MF structures with lateral communication for 100 Mbit/s Ethernet protection have a length of conductors from 1.3 to 2.5 m. In this case, the linear difference of the mode delays in these structures is less than 1 ns/m. In asymmetric structures, the mode delay difference is 3 ns/m. However, such structures are difficult to match, and additional phantom pulses appear in them. Thus, there is a need to find new solutions to reduce the size of the MF and increase the difference in delays of the modes. The elimination of these disadvantages is possible through the use of materials with high and ultra-high dielectric constant [4]. However, this solution is expensive. One of the alternative solutions is the use of structures with a periodic profile of the coupling region of the conductors [5]. In such structures, the length of the differential mode path is increased compared to the common mode, since the currents of the differential mode are displaced to the inner edges of the conductors in the coupling region, and the common mode currents to the outer ones [6]. In this regard, in these constructions, the differential mode pulse comes to the end of the line after the common mode pulse, unlike previously known structures.

The purpose of the work is to present the results on the development of modal filters with an interdigital structure of conductors for 100 Mbit/s Ethernet equipment protection.

II. Printed Modal Filters for Computer Network Protection

At the moment, for the 100 Mb/s Ethernet equipment protection, MFs are used, which consist of three rectangular conductors in cross-section on a dielectric substrate, with active and passive conductors located on one side of it, and the second between them in the center on the reverse. Width of conductors w=0.3 mm, thickness of conductors t=0.105 mm, distance between active and passive conductors s=0.4 mm, substrate with dielectric constant ε_r=4.3 is made of h=0.29 mm fiberglass thick. The cross section of the structure is shown in Fig. 1.

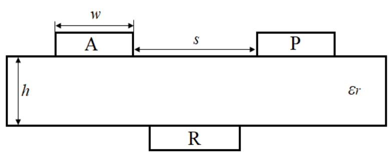

Fig. 1. Cross-section of MF, where A¬active conductor, P-passive conductor and R-reference conductor.

The passive conductor is divided into 7 segments with lengths: 306, 420, 300, 140, 77, 38 and 19 mm, respectively. One of the ends of each of the segments of the passive conductor is connected to the reference conductor through a metallized via. A distinctive feature of this design is the aligned length of the half-turns to reduce the level of radiated emissions. In Fig. 2 presents the MF to the 100 Mb/s Ethernet equipment protection with an aligned half-turn width.

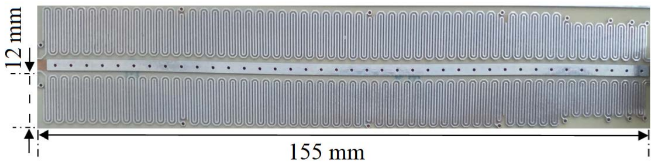

Fig. 2. MF for the protection of the 100 Mbit/s Ethernet equipment with the aligned half-turn width (top view).

An electrodynamic analysis of the passage of an USP with a duration of 0.3 ns and an amplitude of 10 V through the MF was performed. The passive conductor was switched on in a match mode. The simulation was performed using an electrodynamic approach, taking into account losses and without taking into account stages and turns, to be able to determine the total difference between the mode delays. The frequency dependence of the transmission coefficient of the structure is also calculated. Fig. 3 shows the simulation result. It can be seen that the difference in mode delays is 1.2 ns, the bandwidth is 147 MHz, and the resonance is at 460 MHz. Also an electrodynamic analysis of the response to the USP in the seven-stage MF is performed taking into account the effect of coils (Fig. 4*a*). It can be seen that the attenuation is 10 times, but reflections with an amplitude of voltage up to 1.5 V are observed at the input. Fig .4*b* shows the transmission coefficient of the original layout in the frequency range from 0 to 200 MHz. The diagram shows that the bandwidth is 106 MHz.

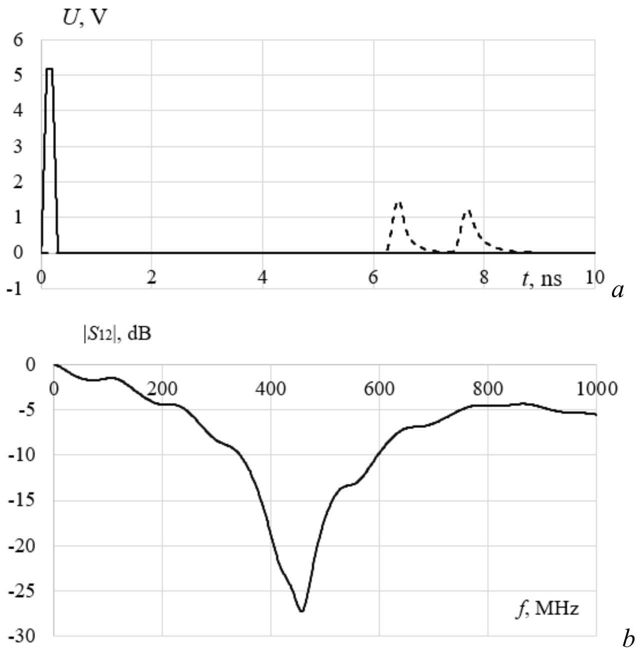

Fig. 3. Voltage waveforms at the beginning (——) and at the end (- - -) of the active conductor of the initial MF (*a*) and and $|S_{12}|$ (*b*)

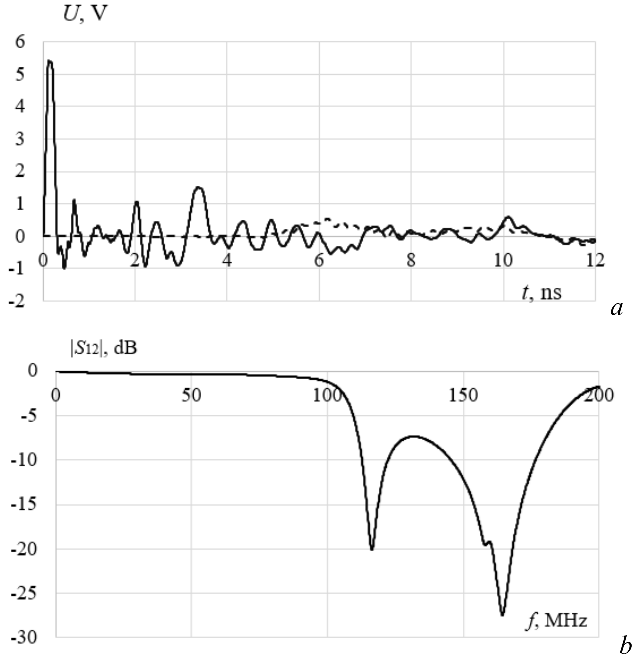

Fig. 4. Voltage waveforms at the beginning (——) and at the end (- - -) of the active conductor of the seven-stage MF (*a*) and $|S_{12}|$ (*b*).

III. Simulation of Resistive MF with Interdigital Structure of Conductors

In [8], MFs with a periodic profile of the conductor coupling region were investigated. mong them, MF with interdigital topology has the simplest construction. This structure has the same values of *h* and *t* as the seven-stage MF. The length of the pins is *lp*=1.4 mm, since it provides the greatest difference in mode delays with the necessary bandwidth.

Next, a parametric optimization of the geometrical parameters *s* and *w* was carried out according to the criteria for increasing the difference in mode delays and preserving the bandwidth. After optimization, a structure was obtained that provides the best time and frequency characteristics with values of *s*=0.384 mm и *w*=0.18 mm. At the same time, the length of the MF conductors is equal to 0.3 m. At this length, the difference of the modes delays of 1.2 ns is ensured, as well as in the seven-stage MF

Fig. 5 shows the structure of an MF with an interdigital topology, where pins with a length of *lp* are added to the active and passive conductors.

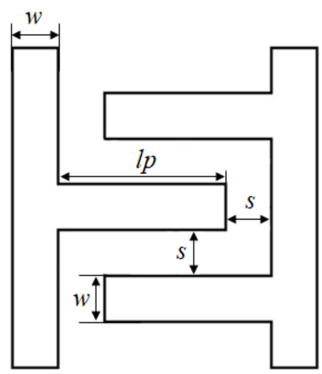

Fig. 5. MF structure with interdigital topology.

Based on the above geometrical parameters, a MF layout with an interdigital topology has been constructed (Fig. 6). For a compact layout design, the shape of the conductors is made in the form of a meander. At the beginning and at the end of the active and passive conductors of the MF model, loads with a resistance of 100 Ohms are connected. The connection scheme of the layout is shown in Fig. 7.

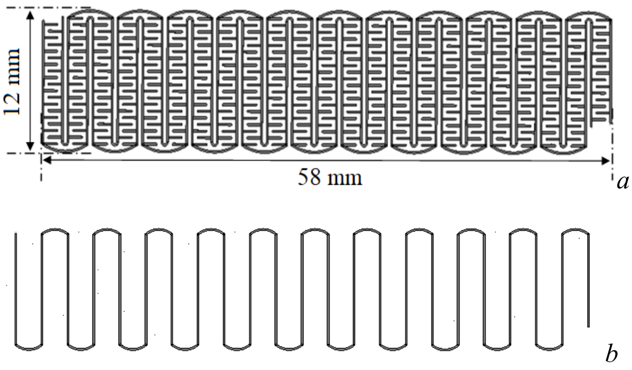

Fig. 6. Resistive single-stage MF conductors with interdigital topology: active and passive (*a*), reference (*b*).

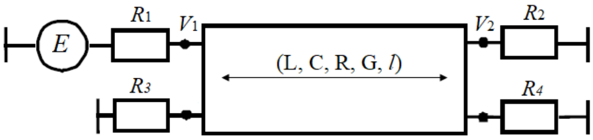

Fig. 7. Connection scheme of the resistive single-stage MF.

When implementing equipment protection of Ethernet 100 Mbit/s, it is necessary to take into account not only the possibility of USP decomposition, but also the ability to provide a filter bandwidth of at least 100 MHz. To check the correctness of the design, an electrodynamic simulation with losses was performed. The frequency dependence of $|S_{12}|$ is shown in Fig. 8. The graph shows that the bandwidth is 157 MHz, the resonance is at a frequency of 435 MHz. To check the possibility of protection from the USP, a trapezoidal pulse with a duration of 0.3 ns and an amplitude of 10 V is applied to the input of the MF. In Fig. 9 presents the voltage waveworms at the beginning and end of the active conductor. The obtained dependences showed that the value of the difference between the mode delays is 1.2 ns. The amplitude of the USP at the input is equal to 5.4 V, the .maximum amplitude of the USP at the output is 1.6 V. Thus, the presented MF reduces the USP by 3.38 times.

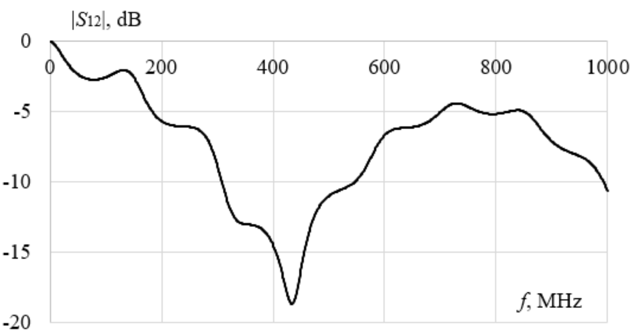

Fig. 8. $|S_{12}|$ of resistive single-stage MF

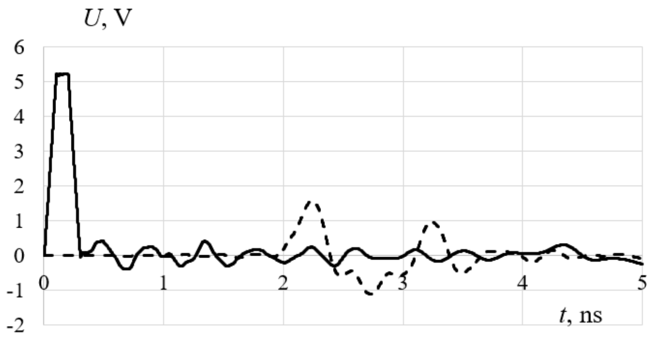

Fig. 9. Voltage waveforms at the beginning (——) and at the end (- - -) of the active conductor of the seven-stage MF with interdigital structure of conductors.

IV. Simulation of Three-Stage Non-Resistive MF with Interdigital Structure of Conductors

To reduce the cost of manufacture and increase the service life of the printed circuit board, a non-resistive MF structure with an interdigital conductor structure is implemented. Layout dimensions are the same as for the resistive single-stage structure. At the same time, in order to achieve an acceptable decomposition of USP, MF is made in the form of three stages. During the implementation of stages, the modes of idling and short circuit (SC) at the beginning and at the end of the passive conductor were used. For this purpose, vias are made for connecting the passive and reference conductors. Thus, the passive conductor in the each stage is included in the idling-SC mode. The length of the conductors of the longest stage was chosen as half the length of the entire MF (l_2=l/2), the length of the second and third cascades as half the length of the second stage (l_1=l_3=l_2/2). However, since the vias can be located only on the outer side of the half-turns, the cascade lengths are equal to l_1=67 mm, l_2=159 mm, l_3=74 mm. The connection scheme of the MF is presented in Fig. 10. The appearance of the active, passive and reference conductors is shown in Fig 11.

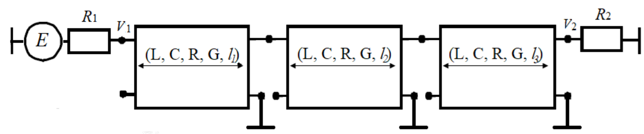

Fig. 10. Connection scheme of three-stage non-resistive MF.

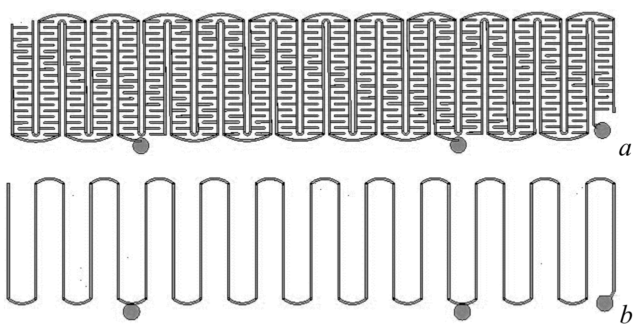

Fig. 11. Conductors of a non-resistive three-stage MF with an interdigital structure: active and passive (*a*), reference (*b*).

The frequency dependence of the transmission coefficient S_{21} of a three-stage resistive MF is shown in Fig. 12. The resulting bandwidth to the first zero frequency is 160 MHz. In Fig. 13 presents the voltage waveforms at the beginning and end of the active conductor. From the dependences obtained, it can be seen that the amplitude of the USP at the input is 5 V, the maximum amplitude of the USP at the output is 1.05 V (attenuation 4.76 times).

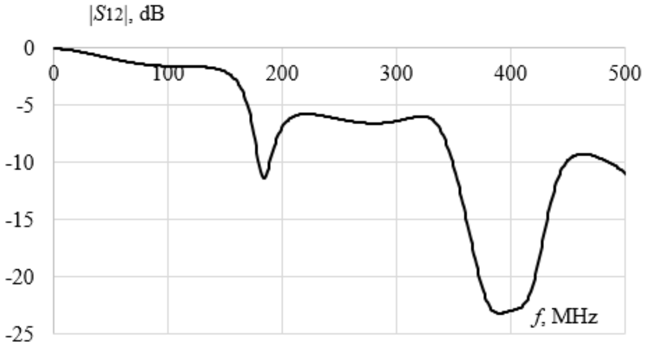

Fig. 12. $|S_{12}|$ of the interdigital non-resistive three-stage MF.

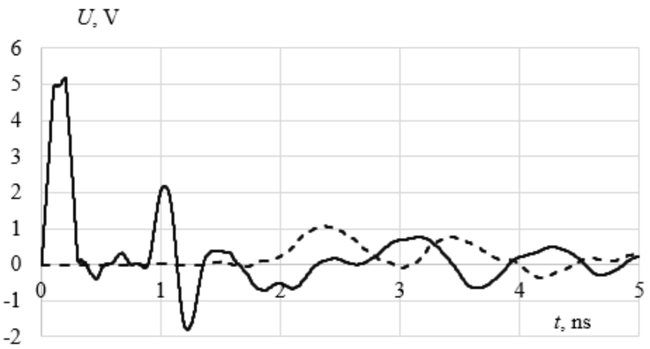

Fig. 13. Voltage waveforms at the beginning (——) and at the end (- - -) of the active conductor of the three-stage MF with interdigital structure of conductors.

V. Conclusion

The paper presents the results of the study of MF with interdigital structure of conductors. Using this topology, it was possible to reduce the length of the MF conductors for 100 Mbit/s Ethernet protection from 1.3 m to 0.3 m or 4.3 times and the layout length from 155 mm to 58 mm or 2.7 times. At the same time, the difference in mode delays remained unchanged (1.2 ns). The bandwidth of the original MF is 106 MHz, of the resistive MF is 157 MHz and of the three-stage non-resistive – 160 MHz. Thus, a significant bandwidth margin was obtained. This leaves possibility for improvement in attenuation of the USP. In practice, more prefered a non-resistive MF, since it has a lower cost of manufacturing a printed circuit board, a longer service life, and a greater attenuation of the USP than a resistive one.

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