# Using Composite Insulating Materials to Improve Modal Filter Performance

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*Abstract* – **This paper presents a new approach for improving modal filter (MF) performance by using composite insulating materials with a relative permeability $\mu_r$>1. The method for making approximate calculations of inductance matrices was validated using simple two-conductor structures as an example. The per-unit-length parameters of the microstrip MF were calculated when the substrate permeability changes. Time responses were obtained for filters of different lengths. The results show that the increase of the substrate permeability leads to the increase of the time intervals between the decomposition pulses. This effect can be used to reduce the MF size or to decompose an ultrashort pulse of longer duration.**

*Index Terms* – **Electromagnetic compatibility, modal filtration, microstrip transmission lines, ultrashort pulse, composite materials.**

## I. INTRODUCTION

AN IMPORTANT TASK of electromagnetic compatibility is to ensure the resistance of radio-electronic equipment (REE) to the effects of conductive interference [1, 2]. Among them ultrashort pulses (USPs), which have a wide spectrum and a minimum signal duration, are especially dangerous [3, 4]. The most promising devices protecting REE against the influence of USPs are modal filters (MFs). The operation of such filters is based on the modal filtration technology, which implies decomposing a USP into a sequence of pulses of lower amplitude. The decomposition of a USP is possible in transmission lines (TL) with inhomogeneous dielectric filling due to the difference in mode delays [5]. A complete USP decomposition in a TL segment of length $l$ occurs if the total pulse duration $t_\Sigma$ is less than the minimum modulus of the difference of mode propagation delays in the line [6], i.e. when

$$t_\Sigma < l\cdot\min|\tau_i - \tau_k|,\quad i, k=1,\ldots, N,\ i\neq k$$

where $\tau_{i\,(k)}$ is per-unit-length delay of the $i(k)^{\text{th}}$ TL mode.

## II. PROBLEM STATEMENT

The simplest structure of a MF is a segment of coupled lines (with the number of conductors $N$=2). In such structures, the input pulse is decomposed into two pulses of lower amplitude. In addition, depending on the electromagnetic coupling and the parameters of the TL, the amplitude of the USP can decrease by more than 2 times relative to the initial value [7]. There are several ways to increase the effectiveness of MFs. For example, due to the sequential pulses division during the cascade connection of two MFs, the USP can be divided into 4 pulses of lower amplitude [8]. The MF characteristics can be improved by changing their cross sections. Thus, an increase in the number of passive conductors of the MF allows decomposing a USP into a larger number of pulses [9]. In this case, pulses with equal amplitudes and time intervals between them can be obtained at the MF output [10] by ensuring simultaneous electromagnetic couplings between the conductor edges and their broad sides (for example, in MFs with reflection symmetry [11]). The improvement of MFs is also possible by changing the topology. For example, in [12] it has been shown that the use of a periodic topology allows increasing the difference in mode delays by up to 2 times relative to the initial filter topology.

In published research [5–12], the effect of modal decomposition is demonstrated on the examples of MFs with a fiberglass as an insulating material. It is also known that the effectiveness of MFs increases when using materials with a high relative permittivity $\varepsilon_r$ (for example, ceramics), which makes it possible to reduce dimensions of MFs. However, in the case of using ceramic insulating material, the manufacturing cost of MFs is significantly increased.

Meanwhile, the possibility of improving MFs through the use of modern composite insulating materials with a relative magnetic permeability $\mu_r$>1 has not been previously considered. The purpose of this work is to study the effect of the parameters of such materials on the characteristics of MFs.

## III. INDUCTANCE CALCULATION

In this paper, to calculate matrices of per-unit-length coefficients of electrostatic (**C**) and electromagnetic (**L**) induction, we used the method of moments implemented in the TALGAT software [13]. The calculations of **L** were performed based on the relation from [14]

$$\mathbf{L} = \varepsilon_0\mu_0\mathbf{C}'^{-1} \tag{1}$$

where $\varepsilon_0$, $\mu_0$ are electric and magnetic constants, respectively; $\mathbf{C}'$ is the matrix of per-unit-length coefficients of electrostatic induction for the initial TL if all $\varepsilon_r$ values of

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the insulating materials are set equal to the reciprocal values of relative permeability $\mu_r$ of these materials, i.e.

$$\varepsilon'_{r(i)} = \frac{1}{\mu_{r(i)}}, \quad i = 1, 2, ..., N$$

where $N$ is the number of insulating materials (with different values of $\varepsilon_r$ and $\mu_r$) used in the studied TL.

To validate (1), the per-unit-length inductance of two-conductor structures shown in Fig. 1 was calculated. We compared the results obtained using (1), analytical expressions from [15] (for structures in Fig. 1*a* and Fig. 1*b*) and the ELCUT software [16] (for the structure in Fig. 1*c*). The results of calculations are presented in Table I.

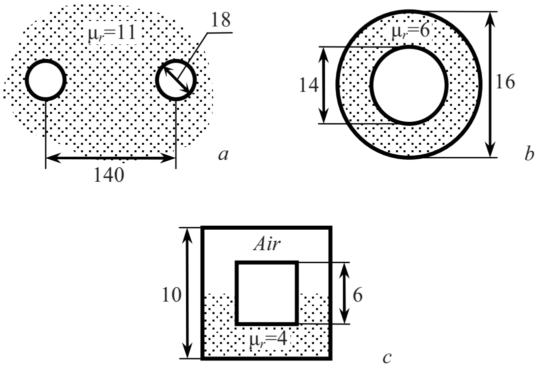

Fig. 1. Test structures (dimensions are in mm).

TABLE I
TEST STRUCTURE PER-UNIT-LENGTH INDUCTANCE CALCULATION RESULTS

| Structure | [14], mH/ m | [15] or [16], mH/m |
|---|---|---|
| Fig. 1*a* | 12.058 | 12.069 |
| Fig. 1*b* | 0.1602 | 0.1601 |
| Fig. 1*c* | 0.1413 | 0.1432 |

Table I shows that the inductance values calculated using [14] and [15, 16] are in good agreement. It means that expression (1) can be used to calculate the inductance matrices **L** with acceptable accuracy.

## IV. ANALYSIS OF PER-UNIT-LENGTH PARAMETERS OF MICROSTRIP MF

A microstrip TL with geometric parameters $s$=0.2 mm, $w$=0.85 mm, $t$=0.035 mm, $h$=0.5 mm was chosen as a test structure to study the influence of insulating material permeability on MF characteristics. The cross-sectional geometry of this line is shown in Fig.2.

For the presented structure, the matrices of the primary per-unit-length parameters **C** and **L** at $\varepsilon_r$=4.5 were calculated without taking into account losses assuming only propagation of T-waves (quasi-static analysis). The $\mu_r$ value ranged from 1 to 10 with a step of 3. The calculation results are presented in Table II, which also shows the values of coupling coefficients $K_L = L_{12}/L_{11}$ and $K = (Z_e/Z_o)^{0.5}$ ($Z_e$, $Z_o$ are the impedances of even and odd modes, respectively).

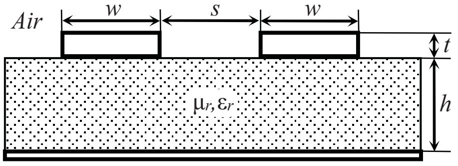

Fig. 2. Cross section of the microstrip MF.

TABLE II
CALCULATION RESULTS of PER-UNIT-LENGTH PARAMETER MATRICES

| $\mu_r$ | **C**, pF/m | **L**, nH/m | $K_L$ | $K$ |
|---|---|---|---|---|
| 1 | $\begin{bmatrix} 122.39 & -23.72 \\ -23.72 & 122.39 \end{bmatrix}$ | $\begin{bmatrix} 302.53 & 91.43 \\ 91.43 & 302.53 \end{bmatrix}$ | 0.302 | 2.00 |
| 4 |  | $\begin{bmatrix} 639.43 & 293.6 \\ 293.6 & 639.43 \end{bmatrix}$ | 0.460 | 1.73 |
| 7 |  | $\begin{bmatrix} 791.74 & 409.8 \\ 409.8 & 791.74 \end{bmatrix}$ | 0.517 | 1.65 |
| 10 |  | $\begin{bmatrix} 884.69 & 485.8 \\ 485.8 & 884.69 \end{bmatrix}$ | 0.549 | 1.61 |

As it can be seen from Table II, a change in the $\mu_r$ value of the substrate does not affect the calculation results of the matrix **C**. Moreover, with an increase in $\mu_r$, the values of the elements located on the main diagonal of the matrix **L** significantly increase. In addition, for $\mu_r$=1, the values of the elements on the side diagonal are higher than for $\mu_r$>1.

With $\mu_r$ increasing, the value of the $K_L$ coefficient increases. It indicates the strengthening of the inductive coupling between the conductors. Meanwhile, the value of $K$ decreases.

## V. TIME RESPONSE SIMULATION OF MICROSTRIP MF

Next, we simulated the time response of the microstrip MF (with different values of $\mu_r$ of the substrate) when the filter length changed ($l$=1, 0.5 and 0.2 m). The schematic diagram of the filter used in the simulation is presented in Fig. 3*a*. The active conductor of the MF was connected to an ideal EMF source with an internal resistance $R_1$. A trapezoidal pulse with a total duration of $t_\Sigma$=150 ps and an amplitude of 5 V was used as an excitation (Fig. 3*b*). The resistance values of $R_1$, $R_2$, $R_3$ and $R_4$ connected at the ends of the filter were set based on the conditions for ensuring pseudo-matching, i.e. when the resistances are equal to the geometric mean value of the impedances $Z_e$ and $Z_o$:

$$R = (Z_e Z_o)^{0.5}.$$

In this case, the voltage amplitude at the beginning of the active filter conductor (point $V_2$ on Fig 3*a*) is equal to half the amplitude of the excitation signal (Fig. 3*b*).

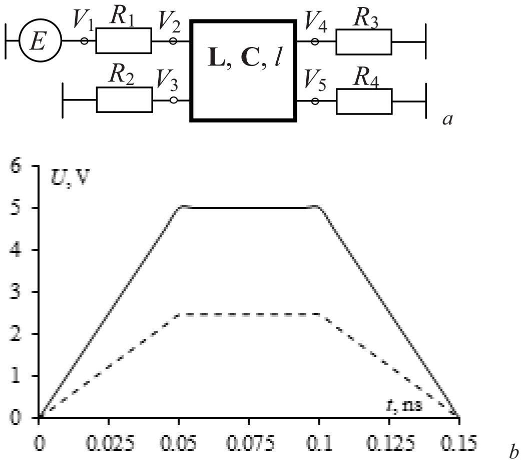

Fig. 3. Schematic diagram of the microstrip MF (*a*) and waveforms of the excitation EMF (—) and signal at the input of the MF (– –) (*b*).

Fig. 4 shows the obtained waveforms of voltages at the output of the microstrip MFs of various lengths with a change in the value of the substrate $\mu_r$. Table III presents the values of the decomposition pulses arrival time and the values of the time interval between them.

### TABLE III
### ARRIVAL TIMES OF PULSES AND TIME DIFFERENCE BETWEEN THEM

| *l*, m | $\mu_r$ | $t_1$, ns | $t_2$, ns | $\Delta t$, ns |
|---|---|---|---|---|
| 1 | 1 | 6.23 | 5.55 | 0.68 |
| | 4 | 9.59 | 7.10 | 2.49 |
| | 7 | 10.88 | 7.47 | 3.41 |
| | 10 | 11.62 | 7.63 | 3.99 |
| 0.5 | 1 | 3.11 | 2.77 | 0.34 |
| | 4 | 4.79 | 3.55 | 1.24 |
| | 7 | 5.44 | 3.73 | 1.71 |
| | 10 | 5.81 | 3.81 | 2 |
| 0.2 | 1 | 1.24 | 1.11 | 0.13 |
| | 4 | 1.91 | 1.42 | 0.49 |
| | 7 | 2.17 | 1.49 | 0.68 |
| | 10 | 2.32 | 1.52 | 0.8 |

The analysis of Fig. 4 and Table III showed that with an increase in $\mu_r$, the time intervals between decomposition pulses significantly increase. Thus, the use of composite insulating materials with $\mu_r>1$ makes it possible to significantly reduce the size of the MF or to decompose a USP of significantly longer duration, compared with a filter on a dielectric substrate with the same length.

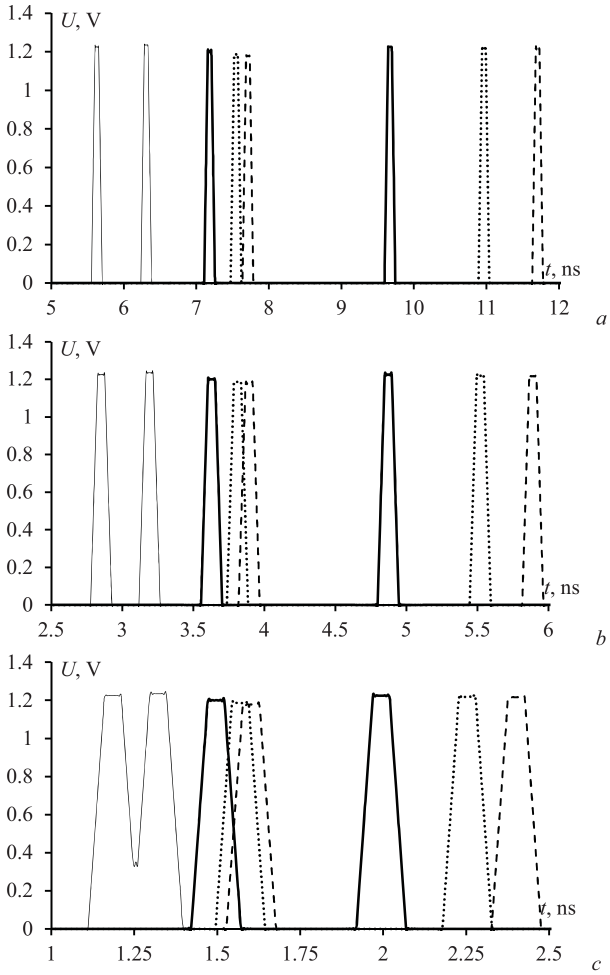

Fig. 4. Waveforms of voltage at the MF output: *a*) *l*=1 m, *b*) *l*=0.5 m, *c*) *l*=0.2 m for $\mu_r$=1 (—), $\mu_r$=4 (—), $\mu_r$=7 (·····), $\mu_r$=10 (– –).

## VI. CONCLUSION

In the course of the study, using the example of three TLs, we validated the method from [14], which allows performing approximate calculations of the matrix **L** for multi-conductor structures taking into account an arbitrary value of insulating material $\mu_r$. The results obtained by using [14] and other sources are in good agreement. This method is used in calculating the per-unit-length parameter matrices of the two-conductor MF with a cross section in the form of a microstrip line.

It is shown that with an increase in $\mu_r$, the values of the elements located on the main diagonal of the matrix **L** significantly increase. The time responses at the output of microstrip MFs of different length were simulated when the $\mu_r$ value of the filter substrate changes. It is shown that with an increase in $\mu_r$ the time interval between decomposition pulses significantly increases. As a result, the modal filter with a length of 0.2 m with a substrate made of composite insulating material (with $\mu_r$=7) has the same characteristics as a filter with *l*=1 m made on a dielectric (with $\mu_r$=1). Thus, the use of composite insulating materials can significantly improve the characteristics of MFs.

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