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Analytical Models and Conditions for Optimal Protective Meander Lines

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ABSTRACT

The paper presents new analytical models for calculating the time response of a meander line (ML) turn with symmetrical cross-section and terminations to a pulse excitation. For the first time, the models were used to derive simple analytical models to equalize voltage amplitudes of the first pulses at the ML turn output: two pulses in homogeneous and three pulses in inhomogeneous dielectric filling. The obtained models were validated by quasistatic simulation. As a result, we theoretically proved that the maximum pulse amplitudes at the ML output are equal to 61.8% and 41.4% of the input amplitudes for the lines with homogeneous and inhomogeneous dielectric filling, respectively. The results could considerably simplify a computer-aided design, allowing for accelerated optimization of these structures without costly multivariate calculation of time response by numerical methods.

***Index Terms*—**Analytical models, even mode, odd mode, meander line, protective device.

I. INTRODUCTION

Meander lines (MLs) are a common component of printed circuit boards (PCBs) in modern devices. MLs have also found application in receiving and transmitting antennas [1], inductors [2], multilayer capacitors [3], filtering devices [4], devices for correcting group delay time, and phase correctors [5].

Most studies of MLs aim to minimize useful signal distortions that arise from cross-couplings. Since, in its first approximation, an ML can be represented by a set of pairs of coupled lines, the numerical methods developed for coupled lines are used to analyze ML parameters. However, the use of these methods is not always advisable. For example, in a number of special cases (with negligible loss and dispersion), the computational costs of simulation by a numerical method are high (especially in case of optimization). In these situations, it is reasonable to use analytical models for quick estimates that also provide acceptable accuracy. For example, crosstalk, signal propagation delay, and pulse distortions in interconnects can be analyzed with the approach proposed in [6]. The transfer functions of *N* coupled interconnects with arbitrary impedances at the ends can be determined by using the expressions in a closed form, as in [7]. In addition, noteworthy are models based on the numerical inverse Laplace transform [8, 9], and analytical models for periodic multistage structures of single and coupled lines [10].

One of the new applications of MLs is the protection against an ultrashort pulse (USP) by its decomposition into pulses with equal and lower amplitudes. The pulse is decomposed into two main pulses in an air-filling line [11], into three pulses in a microstrip line [12], and into four pulses in an asymmetric cross-section line [13]. The specificity of the result of the USP's excitation is that the coupling from it can be perceived as useful signals, destroying digital exchange, and can penetrate through traditional protection means and lead to failure [14]. Decreasing the resulting amplitude of the interference to a safe level with new devices (single or connected in cascade) instead of or in addition to well-known devices, can improve the protection. Therefore, engineers and researchers are actively investigating and developing new devices that enable weakening the impact of USPs by their decomposition into pulses with lower amplitudes (minimum when they are equalized). One example of such devices is a modal

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filter [15]. Meanwhile, the protective MLs are very similar to modal filters [16, 17] and can even be superior, since they provide a larger number of decomposition pulses, a doubled propagation path along the ML, and the absence of resistive components [11-13]. Thus, the study and application of MLs to protect equipment against USPs is relevant.

In the noted studies of protective MLs, the analysis was performed in the frequency domain based on algorithmic mathematical models. However, the use of such models is costly, especially if it is necessary to optimize the lines in order to equalize and minimize the amplitudes of the decomposed pulses [18]. Therefore, it is important to obtain simple analytical models for quick and a priori estimates of the pulse amplitudes and also the conditions for their equalization. The aim of this paper is to do this for cases of two and three pulses decomposed in a turn of an ML.

II. INITIAL DATA

Fig. 1 shows a circuit diagram of the ML under investigation.

It consists of a reference and two signal parallel conductors with the length l, interconnected at one end. One of the signal conductors is connected to the emf. source E with internal admittance Y_0, while the other is connected to the load Y_0. Since the signal at the ML end is represented as a sequence of main pulses, first it is necessary to analytically obtain the amplitude of each of the pulses. For this, it is convenient to use analytical models for one segment of a symmetric coupled transmission line obtained on the basis of models for a single line with admittance Y_1 and per-unit-length delay τ_1 (see Fig. 2) [10].

To make further discourse clear, we will first present these models. The response components at the far (considering the transmitted wave) and near (considering the reflections from the beginning and end of the line segment) ends of the structure are:

$$V_0(t)=\frac{2Y_0}{Y_0+Y_1}\frac{2Y_1}{Y_1+Y_2}V_{in}(t-l\tau_1), \tag{1}$$

$$V_1^{'}(t)=\frac{Y_0-Y_1}{Y_0+Y_1}V_{in}(t), \tag{2}$$

$$V_1^{''}(t)=\frac{2Y_0}{Y_0+Y_1}\frac{2Y_1}{Y_0+Y_1}\frac{Y_1-Y_2}{Y_2+Y_1}V_{in}(t-2l\tau_1). \tag{3}$$

The expressions, when the numbers of reflections (k_{ref}) are set, allow us to calculate the response at the far (which consider the components that experienced an even number of reflections) or near (which consider the components that experienced an odd number of reflections) ends of the line:

$$V_T(t)=V_0(t)+\sum_{k=1}^{k_{ref}/2}V_{outK}(t), \tag{4}$$

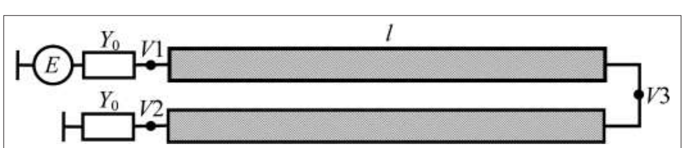

Fig. 1. Circuit diagram of the ML turn.

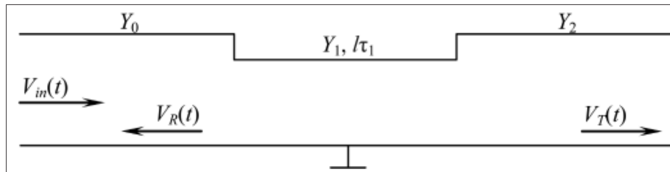

Fig. 2. Equivalent circuit of the transmission line segment with terminations.

$$V_R(t)=V_1^{'}(t)+V_1^{''}(t)+\sum_{k=1}^{(k_{ref}-1)/2}V_{refK}(t), \tag{5}$$

where

$$V_{outK}(t)=\frac{2Y_0}{Y_0+Y_1}\frac{2Y_1}{Y_1+Y_2}V_{in}\left(t-(2k+1)l^{\sim}{}_{1}\right)\prod_{i=1}^{k}\frac{Y_1-Y_2}{Y_1+Y_2}\frac{Y_1-Y_0}{Y_0+Y_1}, \tag{6}$$

$$V_{refK}(t)=\frac{2Y_0}{Y_0+Y_1}\frac{2Y_1}{Y_0+Y_1}\frac{Y_1-Y_2}{Y_1+Y_2}V_{in}\left(t-2(k+1)l^{\sim}{}_{1}\right)\prod_{i=1}^{k}\frac{Y_1-Y_2}{Y_1+Y_2}\frac{Y_1-Y_0}{Y_0+Y_1}. \tag{7}$$

Expressions (1)–(7) for a single line are applicable for a symmetrical (in cross-section and on loads) coupled line if we write them separately, replacing index "*1*" in Y_1 and τ_1 with indices "*e*" and "*o*" for the even and odd modes, respectively. Then, when the voltage at the beginning of the active conductor $V_{in}(t)$ is equal to half the exciting emf., the response components for the even and odd modes can give the responses at each node of the coupled line

$$V_1(t)=\frac{1}{2}\left[V_R^e(t)+V_R^o(t)\right], \tag{8}$$

$$V_2(t)=\frac{1}{2}\left[V_R^e(t)-V_R^o(t)\right], \tag{9}$$

$$V_3(t)=\frac{1}{2}\left[V_T^e(t)+V_T^o(t)\right], \tag{10}$$

$$V_4(t)=\frac{1}{2}\left[V_T^e(t)-V_T^o(t)\right], \tag{11}$$

where $V_1(t)$ and $V_3(t)$ are the responses at the beginning and end of the active conductor, and $V_2(t)$ and $V_4(t)$ are responses of the passive conductor.

III. MODELS FOR CALCULATING THE TIME RESPONSE IN THE ML TURN

The structure in Fig. 1 is a coupled line with conductors without terminations and interconnected at the far end. Then, for the far end (in Fig. 2 and in (1–2)), $Y_2=\infty$ for the odd mode, and $Y_2=0$ for the even mode. Then, expressions (1–7) for each mode will be greatly simplified. Using (8–11), we obtain the final expressions for calculating the responses at nodes V_1, V_2, and V_3:

$$\begin{aligned}V_1(t)=&\frac{V_{in}(t)}{2}\left(\frac{Y_0-Y_e}{Y_0+Y_e}+\frac{Y_0-Y_o}{Y_0+Y_o}\right)+2Y_0\left(\frac{Y_eV_{in}(t-2l\tau_e)}{(Y_e+Y_0)^2}-\frac{Y_oV_{in}(t-2l\tau_o)}{(Y_o+Y_0)^2}\right)\\&+2Y_eY_0\sum_{i=2}^{k_{ref}}(-1)^{i+1}V_{in}(t-2l\tau_e i)\times(Y_e+Y_0)^{-(1+i)}(Y_0-Y_e)^{i-1}\\&-2Y_oY_0\sum_{i=2}^{k_{ref}}V_{in}(t-2l\tau_o i)\times(Y_o+Y_0)^{-(1+i)}(Y_0-Y_o)^{i-1},\end{aligned} \tag{12}$$

$$V_2(t)=\frac{V_{in}(t)}{2}\left(\frac{Y_0-Y_e}{Y_0+Y_e}-\frac{Y_0-Y_o}{Y_0+Y_o}\right)+2Y_0\left(\frac{Y_eV_{in}(t-2l\tau_e)}{(Y_e+Y_0)^2}+\frac{Y_oV_{in}(t-2l\tau_o)}{(Y_o+Y_0)^2}\right)$$
$$+2Y_eY_0\sum_{i=2}^{k_{ref}}(-1)^{i+1}V_{in}(t-2l\tau_e i)\times(Y_e+Y_0)^{-(1+i)}(Y_0-Y_e)^{i-1}$$
$$+2Y_oY_0\sum_{i=2}^{k_{ref}}V_{in}(t-2l\tau_o i)(Y_o+Y_0)^{-(1+i)}(Y_0-Y_o)^{i-1}, \tag{13}$$

$$V_3(t)=V_4(t)=\frac{2Y_0V_{in}(t-l\tau_e)}{(Y_e+Y_0)}$$
$$+2Y_0\sum_{i=2}^{k_{ref}}(-1)^{i+1}V_{in}\big(t-l\tau_e(2i-1)\big)(Y_e+Y_0)^{-i}(Y_0-Y_e)^{i-1}. \tag{14}$$

To verify expressions (12–14), we calculated the time responses at circuit nodes V_1, V_2, and V_3 (Fig. 2) to the USP excitation (Fig. 3) in the TALGAT software by a numerical method in the frequency domain [19]. The parameters of the ML cross-section, the source, and the load are taken from [12]. The obtained waveforms completely coincide.

From (13), it is easy to get the analytical expressions of the normalized amplitudes of first (crosstalk – V_c), second (odd mode – V_o), and third (even mode – V_e) pulses at the ML output

$$V_c=\frac{Y_0(Y_o-Y_e)}{(Y_o+Y_0)(Y_e+Y_0)}, \tag{15}$$

$$V_o=\frac{2Y_0Y_o}{(Y_o+Y_0)^2}, \tag{16}$$

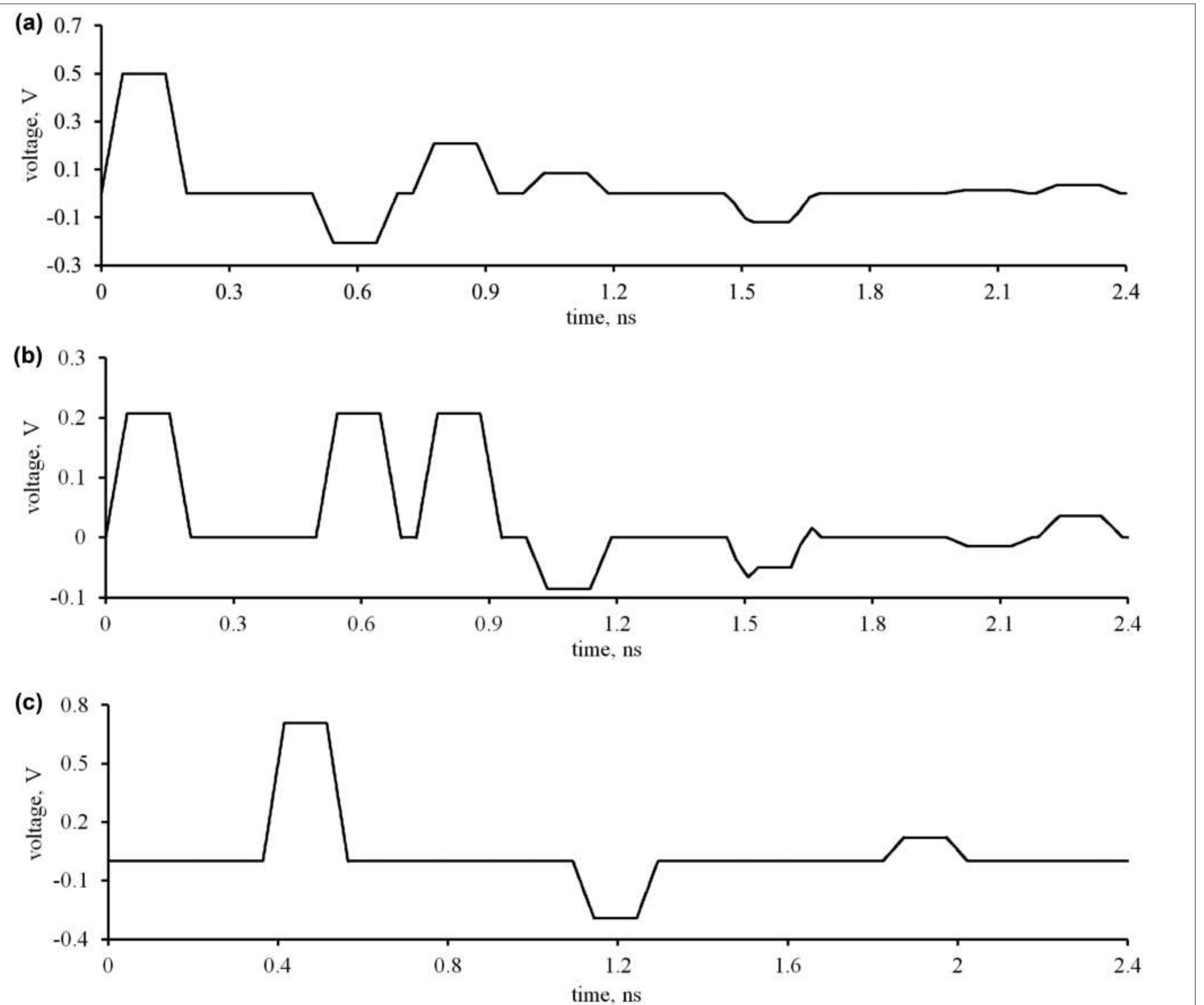

Fig. 3. Voltage waveforms at nodes V_1 (*a*), V_2 (*b*), and V_3 (*c*) of the circuit in Fig. 1 calculated using expressions (12–14) (- -) and with TALGAT.

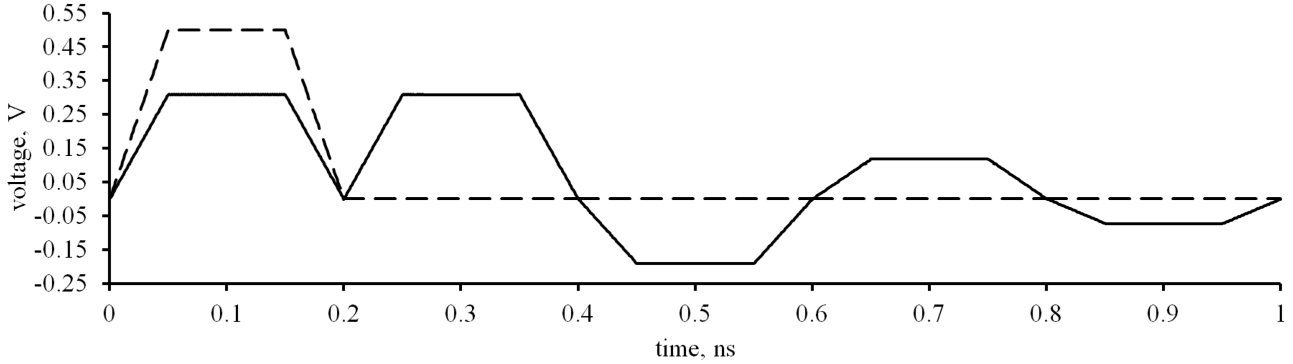

Fig. 4. Voltage waveforms at nodes V_1 (– –) and V_2 (––) of the ML in the air filling when k≈4.236.

$$V_e = \frac{2Y_0Y_e}{(Y_e+Y_0)^2} \tag{17}$$

and formulate the conditions for the equality of pulse amplitudes.

IV. EQUALIZING THE TWO OUTPUT PULSE AMPLITUDES

If the per-unit-length delays of the even and odd line modes are the same, their pulse amplitudes are summed. Then, from $V_c = V_o + V_e$ and (15), we obtain $(Y_o+3Y_e)/Y_0+(3Y_0+Y_e)/Y_o+(Y_0-Y_o)/Y_e=-8$.

We consider a special case of minimizing signal reflections at the ends of the conductors when $Y_0=\sqrt{(Y_eY_o)}$. Then, after substituting $k = \sqrt{(Y_o/Y_e)}$, which has the physical meaning of the coupling coefficient, we obtain the biquadratic equation $k^4-2k^3-8k^2-6k-1=0$, having one physical root $k=\sqrt{5}+2 \approx 4.236$, which determines the normalized amplitude at the ML end as $(k-1)/(k+1)=(\sqrt{5}-1)/2 \approx 0.618$.

For verification, we calculated the matrices and the time responses at nodes V_1 and V_2 to the USP excitation in the TALGAT software. The parameters of the excitation, line cross-section, source, and loads are taken from [11]. Matrices **C** [pF/m], **L** [nH/m], and **Z** [Ohm] are the following:

$$\begin{bmatrix} 153.16 & -137.00 \\ -137.00 & 153.16 \end{bmatrix};\begin{bmatrix} 363.35 & 325.01 \\ 325.01 & 363.35 \end{bmatrix};\begin{bmatrix} 108.93 & 97.44 \\ 97.44 & 108.93 \end{bmatrix}.$$

We calculated the impedances of the odd and even modes from matrix **Z** ($Z_o=11.496$ Ohm and $Z_e=206.365$ Ohm) that ensure the condition $k=\sqrt{(Z_e/Z_o)} \approx 4.236$. Fig. 4 shows the waveforms at nodes V_1 and V_2. The first two pulses at the end of the turn have the same amplitudes that are equal to 61.8% of the input level. A single pulse in Fig. 4 at node V_1 is the excitation. The first pulse in Fig. 4 (at node V_2) is crosstalk. The second pulse is the sum of the pulses of the even and odd modes, since they propagate in the ML with a homogeneous dielectric filling with the same delay.

V. EQUALIZING THE THREE OUTPUT PULSE AMPLITUDES

For differing per-unit-length delays of even and odd line modes, their pulses can be separate. Then, equating their amplitudes ($V_o=V_e$ from (15)), we obtain

$$Y_0=\sqrt{(Y_eY_o)}. \tag{18}$$

From the condition of equality of the first and second pulse amplitudes ($V_c=V_o$), we obtain $(Y_o-3Y_e)/Y_0+Y_e/Y_o=1$.

Considering (18) and substituting $k=\sqrt{(Y_o/Y_e)}$, we obtain the cubic equation $k^3-k^2-3k-1=0$ that has one physical root $k=\sqrt{2}+1 \approx 2.413$ which determines the normalized amplitude at the ML end as $(k-1)/(k+1)=\sqrt{2}-1 \approx 0.414$.

For verification, the parameters of the excitation, line cross-section, source, and loads are taken from [12]. Matrices **C** [pF/m], **L** [nH/m], and **Z** [Ohm] are the following:

$$\begin{bmatrix} 232.07 & -138.12 \\ -138.12 & 232.07 \end{bmatrix};\begin{bmatrix} 390.34 & 309.03 \\ 309.03 & 390.34 \end{bmatrix};\begin{bmatrix} 50.55 & 35.73 \\ 35.73 & 50.55 \end{bmatrix}.$$

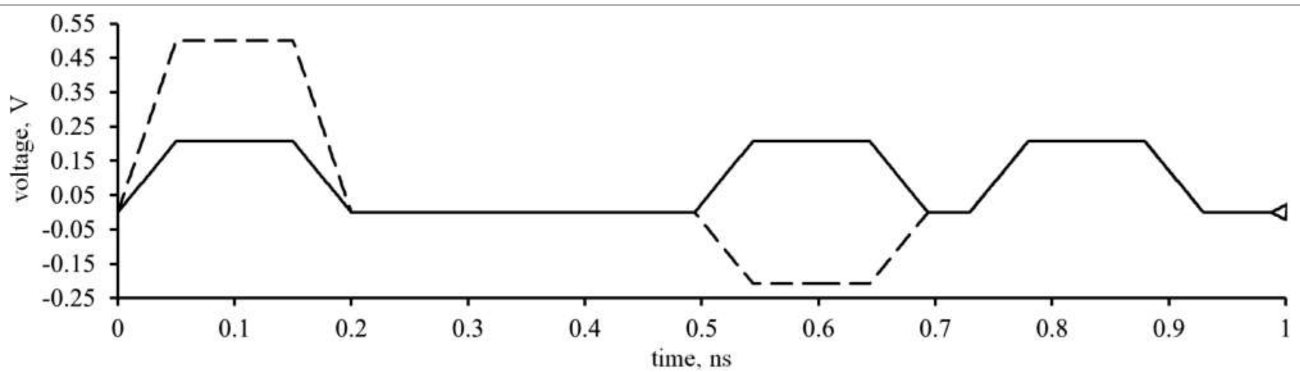

Fig. 5. Voltage waveforms at nodes V_1 (– –) and V_2 (––) of the microstrip ML turn when k≈2.413.

We calculated the odd and even mode impedances from matrix **Z** (Z_o = 14.822 Ohm and Z_e = 86.282 Ohm) that ensure the condition $k = \sqrt{(Z_e/Z_o)} \approx 2.413$. Fig. 5 shows the waveforms at nodes V_1 and V_2. The first three pulses at the end of the turn have the same amplitudes that are equal to 41.4% of the input level. The first pulse in Fig. 5 (at node V_2) is crosstalk. The second pulse is an odd-mode pulse, and the third is an even-mode pulse.

VI. CONCLUSION

Analytical models for calculating the response to the time domain excitation of an ML turn with symmetrical cross-section and terminations were obtained and verified. The models allowed obtaining the condition (in particular case of matching) for one and two pulse amplitudes to be equalized after decomposing a USP at the end of the ML turn with homogeneous and inhomogeneous dielectric filling, respectively. The obtained analytical models and estimations were verified by quasistatic simulation. As a result, we theoretically proved that the maximum amplitude at the end of the ML equals 61.8% and 41.4% of the input amplitude for the lines with homogeneous and inhomogeneous dielectric filling, respectively.

The obtained analytical models and conditions could considerably simplify computer-aided design, allowing for accelerated optimization of these structures without costly multivariate calculation of time response by numerical methods. Moreover, the obtained models and conditions could completely exclude calculating the response from optimization process that is used to equalize pulse amplitudes. The main outcome of the paper is that the new results supplement the theoretical framework of the ML analysis and optimization, and can be used to perform accelerated design of delay lines and create protective devices for arbitrary line cross-sections and excitation pulse waveforms.

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