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The Influence of Non-Uniformity of the Multi-Conductor Line Parameters on Frequency Responses of the Meander Delay Line

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***Abstract*—Inhomogeneities of the electromagnetic field are observed at the edges of the electrodynamic delay systems which are designed based on the concept of periodic multiconductor line. The inhomogeneity manifests itself as a non-uniformity of the characteristic impedance and the effective permittivity of the multiconductor line consisting of a finite number of conductors. The influence of non-uniformity of impedance and effective permittivity of the multiconductor microstrip line on the frequency responses and characteristics of meander delay lines is studied in this paper. It is shown that matching characteristic impedance and effective permittivity of the multiconductor line the bandwidth of the delay line can be extended and delay time increased preserving its dimensions.**

***Index Terms*—effective permittivity, impedance matching, meander delay lines, method of multiconductor line, mode matching.**

I. INTRODUCTION

Delay lines (DL) are widely used in electronic systems for various purposes, e.g. analogue signal processing [1, 2], analog-to-digital converters [3], synchronization of signals [4], to shape radiation pattern of antenna arrays [5, 6], filter design [7] and as a substantial part in many other devices [8–14].

At present, the DLs, based on active components, are popular [9, 11]. Despite that, the electrodynamic DLs have significant advantages like linearity of responses and stability of characteristics [10, 12]. Delay of signals in electrodynamic DLs is caused by propagation of an electromagnetic wave for the prescribed finite time interval – delay time. In order to increase the delay time of the DLs and preserve their dimensions, the length of the electromagnetic wave propagation pathway is increased by shaping a transmission conductor of the DL into a meander or helical line. Thus electrodynamic DLs have periodic structure with a specific repetition period of the meander strips or helical loops; therefore the multiconductor line method is widely used for the analysis and modelling of such lines [15]. The multi-conductor line method is notable for its modest demand of computer resources, which is very important for DL synthesis [14–16]. According to this method the multiconductor line and the corresponding analysed DL are both periodic, therefore theoretically infinite, and consist of the infinite number of evenly spaced conductors of equal widths.

Real DLs having finite dimensions, based on such infinite periodic multiconductor lines have non-uniform parameters on the side conductors due to electromagnetic field spread [17].

The influence of non-uniformity of the multiconductor microstrip line (MCML) parameters on the responses of the meander microstrip delay line (MMDL) is studied in this paper. The generalized structure of the MMDL is presented in Fig. 1. It consists of a dielectric substrate, on one side of which is a conductive layer, and a meander-shaped transmission conductor on the other. According to the multiconductor line method, such MMDL is modelled using the MCML, structure of which is shown in Fig. 2 (a). Thickness h and permittivity ε_r of the dielectric substrate of the MCML is the same as those of the MMDL substrate, moreover, width W of the conductors of the MCML and space S between them are also equal to the corresponding dimensions of the MMDL signal conductor. For the mathematical model, MCML is considered infinite in both – x and z directions. A meander structure is derived from the MCML by separating the section of length $2A$ in x direction and accordingly connecting the ends of the obtained conductor strips (Fig. 2 (b)).

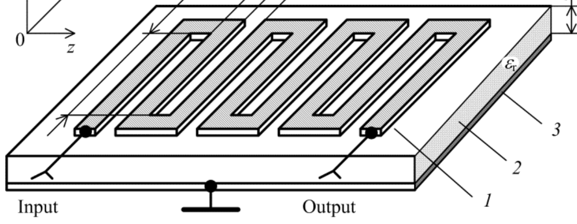

Fig. 1. The structure of the ordinary microstrip meander delay line, where 1 is a signal conductor in the form of meander; 2 is a dielectric substrate; 3 is a reference conductor.

Two kinds of non-uniformity appear in real MMDLs based on the mathematical model of the MCMLs:

– non-uniformity of characteristic impedance $Z_i \neq Z_j$,
– non-uniformity of effective permittivity $\varepsilon_{\mathrm{r\,eff}\,i} \neq \varepsilon_{\mathrm{r\,eff}\,j}$,

where i and j are numbers of conductors of the MMDL, and

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$i \neq j$ for both cases. These kinds of non-uniformity are caused by equal widths of all strips of the meander conductor according to widths of the conductors of the corresponding periodic MCML.

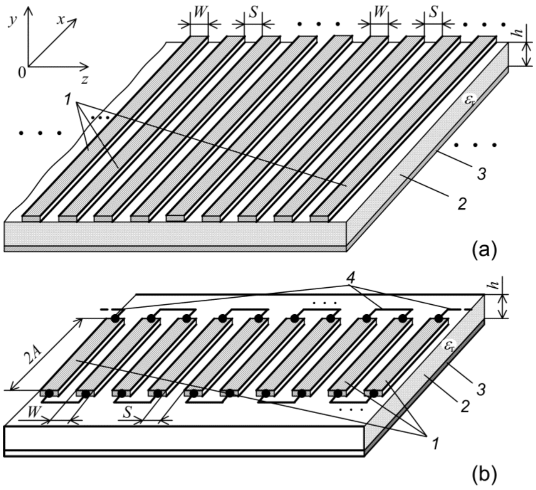

Fig. 2. The generalized structure of the microstrip multiconductor line (a), and microstrip meander structure (b), where 1 are conductors of the line; 2 is a dielectric substrate; 3 is a reference conductor; 4 are connectors of the meander strips.

The technique used to investigate the influence of non-uniformity of the MCML parameters on responses of the MMDL is further described. MCML of uniform characteristic impedance $Z_i = Z_j$ [18], or MCML of uniform effecttive permittivity $\varepsilon_{\mathrm{r\,eff}\,i} = \varepsilon_{\mathrm{r\,eff}\,j}$ [19] is synthesized by employing algorithms created by authors. Further, the corresponding MMDL is created in Sonnet® software environment, using dimensions of the synthesized MCML, and responses of this MMDL are calculated. The calculated responses are compared with those of the MMDL with equal widths of the conductors. The assumption is made in this paper that conductors and dielectric substrates of the synthesized MCMLs and investigated MMDLs are ideal lossless, and it is also assumed that the thickness of the conductors is zero.

II. THE INFLUENCE OF CHARACTERISTIC IMPEDANCE NON-UNIFORMITY ON FREQUENCY CHARACTERISTICS OF THE MEANDER MICROSTRIP DELAY LINE

In order to match any transmission line, including the MMDL, with the remaining signal transmission path, impedances of the MMDL and the path must be equal. It has already been noted in introduction, that designing the MMDL according to the multiconductor line method, it is supposed, that the impedance of all meander strips is uniform (identical) and their widths W are also identical (Fig. 1). However, real MMDLs have finite number of meander strips, therefore inhomogeneity of an electric field takes place on the side strips, resulting in different impedances of side and inner strips (Fig. 3). In this case the signal transmission path and the MMDL are mismatched.

An example of frequency responses of S21 parameter of the investigated MMDLs is shown in Fig. 4. It is seen from the magnitude responses of S21 parameter (Fig. 4(a)) that resonance appears in the MMDL. Frequencies of these resonances are related to the wavelength of the electromagnetic wave propagating in the MMDL and may be approximated by the following equation

$$f_k = \frac{c_0 k}{\sqrt{\varepsilon_{\mathrm{reff}}}\left(2 \cdot 2A + S\right)}, \tag{1}$$

where c_0 is the velocity of light in free space, k is a serial number of resonance, $\varepsilon_{\mathrm{r\,eff}}$ is relative effective permittivity of the MCML, $2A$ and S are dimensions of the meander topology (Fig. 1). It is seen in Fig. 4 (a) that resonances of the uniform impedance MMDL are shifted slightly towards higher frequency (thus expanding bandwidth of the MMDL) with respect to the resonances of the non-uniform impedance MMDL. This shift may be explained by the fact that the effective permittivity $\varepsilon_{\mathrm{r\,eff}}$ of the narrower side strips is lower in case of uniform impedance MMDL, and therefore according to (1) resonance frequency is increased.

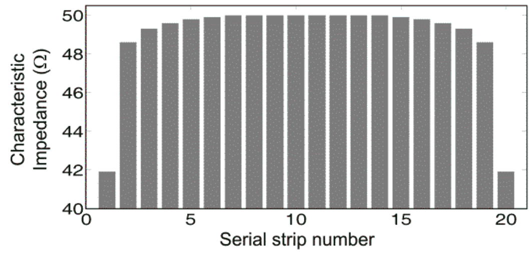

Fig. 3. Non-uniform characteristic impedance of the MMDL designed on the basis of the periodic multiconductor microstrip line at $\varepsilon_r = 9.6$, $h = 0.5$ mm, $W = 0.6$ mm, $S = 0.5$ mm, $2A = 20$ mm, $N = 20$.

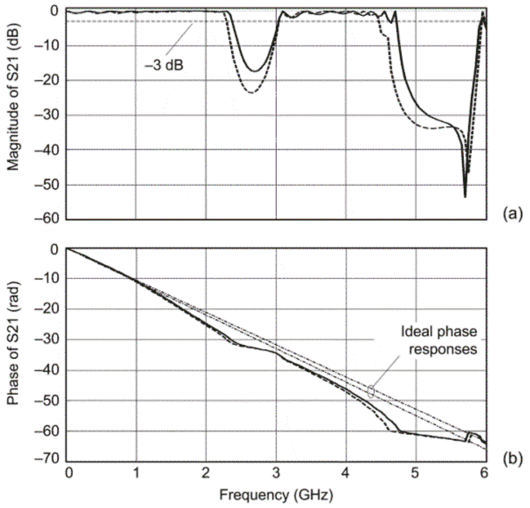

Fig. 4. Magnitude (a) and phase (b) response of parameter S21 of the MMDL which design parameters are following: $\varepsilon_r = 9.6$, $h = 0.5$ mm, $2A = 20$ mm, $N = 10$. Solid curves correspond to the MMDL of uniform impedance, and dashed ones correspond to the MMDL of non-uniform impedance.

The passband bandwidth of the linear time-invariant systems, MMDLs belong to these systems, is usually defined by the frequencies for which the magnitude response is –3 dB [20]. However the bandwidth of the MMDL due to the strong coupling between the strips of meander is determined by phase response distortions, rather than amplitude. E.g. bandwidth of the uniform impedance MMDL, determined according to the amplitude response (magnitude of S21) (Fig. 4(a)), is equal to 2.38 GHz, and bandwidth, determined according to the phase response (angle of S21) (Fig. 4(b)), is equal to 1.1 GHz only. Therefore, in further investigations of the influence of characteristic impedance non-uniformity on frequency characteristics of the MMDL, the passband bandwidth of the MMDL will be considered as a range of frequencies, where difference between the angle of S21 and ideal phase response is less than 0.5 radians.

Delay time t_d and bandwidth ΔF are those critical characteristics that determine the structure of the MMDL. The permittivity of the dielectric substrate ε_r, number of meander strips N and their length $2A$ have the most effect on these characteristics. It should also be noted, that the above mentioned characteristics t_d and ΔF are inversely related, i.e. changing the design parameters of the MMDL in order to increase its delay time, the bandwidth is narrowed and vice versa. Therefore, in order to unambiguously determine the effect of design parameters on the characteristics of the MMDL it is preferable to use the integrated measure of the DL quality – so-called D-factor, which is calculated as the product of delay time of the MMDL and its bandwidth

$$D_{(\mathrm{u,\,u\text{-}n})} = t_{\mathrm{d(u,\,u\text{-}n)}} \cdot \Delta F_{(\mathrm{u,\,u\text{-}n})}, \tag{2}$$

where bottom index (u) means the uniform parameters MMDL (i.e. uniform impedance or uniform effective permittivity of the MCML), and index (n-u) means the non-uniform parameters MMDL (i.e. non-uniform impedance or non-uniform effective permittivity of the MCML).

In the first part of investigations, the effect of matching of characteristic impedances of the MMDL strips on characteristics of these lines is investigated. Dependences of the characteristics of uniform and non-uniform impedance MMDLs on their design parameters are presented in Table I–Table IV. Relative differences between the characteristics of the uniform and non-uniform impedance MMDLs are also presented. The differences are calculated as follows: delay time relative difference

$$\delta t_{\mathrm{d}} = \frac{t_{\mathrm{d(u)}} - t_{\mathrm{d(n\text{-}u)}}}{t_{\mathrm{d(n\text{-}u)}}} 100\%, \tag{3}$$

where $t_{\mathrm{d(u)}}$ is time delay of the uniform parameters MMDL, and $t_{\mathrm{d(n\text{-}u)}}$ is time delay of the non-uniform parameters MMDL; bandwidth relative difference

$$\delta \Delta F = \frac{\Delta F_{(\mathrm{u})} - \Delta F_{(\mathrm{n\text{-}u})}}{\Delta F_{(\mathrm{n\text{-}u})}} 100\%, \tag{4}$$

where $\Delta F_{(\mathrm{u})}$ is bandwidth of the uniform parameters MMDL, and $\Delta F_{(\mathrm{n\text{-}u})}$ is bandwidth of the non-uniform parameters MMDL; MMDL D-factor relative difference

$$\delta D = \frac{D_{(\mathrm{u})} - D_{(\mathrm{n\text{-}u})}}{D_{(\mathrm{n\text{-}u})}} 100\%, \tag{5}$$

where $D_{(\mathrm{u})}$ is the D-factor of the uniform parameters MMDL, and $D_{(\mathrm{n\text{-}u})}$ is the D-factor of the non-uniform parameters MMDL.

Analysis of Tables I–IV reveals that under otherwise identical conditions, delay time $t_{\mathrm{d(u)}}$ of the uniform impedance MMDL is always less than the delay time $t_{\mathrm{d(n\text{-}u)}}$ of non-uniform impedance MMDL. This difference is caused by the lower effective permittivity of the side strips of the uniform impedance MMDL than that of the side strips of the non-uniform impedance MMDL. As a result, the electromagnetic wave along the strips having less effective permittivity is propagating faster and delay time of such MMDL decreases.

It is naturally that the MMDL consisting of more meander strips N, has higher delay time, almost proportionally to N (Table I). Whereas the bandwidth of the MMDL with more meander strips is considerably narrower. It is necessary to note, that the equalization of the MMDL strips impedance has a positive effect only when the number of strips is large as well. It can be seen in Table I that, when $N = 20$, the bandwidth of the uniform impedance MMDL is more than twice wider than the bandwidth of the non-uniform impedance MMDL, and thus D-factor $D_{(\mathrm{u})}$ of the uniform impedance MMDL is also twice better than $D_{(\mathrm{n\text{-}u})}$. However, with a sufficiently large number of menders strips, for example $N = 40$, i.e. when the structure of the MMDL approaches the periodic, the difference between the characteristics of the uniform impedance MMDL and the non-uniform impedance MMDL diminishes (see right column of Table I).

TABLE I. DEPENDENCE OF CHARACTERISTICS OF THE MMDL ON NUMBER OF THE MEANDER STRIPS AT $\varepsilon_r = 9.6$, $h = 0.5$ mm, $2A = 20$ mm.

Characteristic of the MMDL	**Number of meander strips, *N***				
	3	5	10	20	40
$t_{\mathrm{d(u)}}$ (ns)	0.46	0.87	1.68	3.3	6.54
$t_{\mathrm{d(n\text{-}u)}}$ (ns)	0.52	0.92	1.75	3.4	6.69
δt_{d} (%)	–11	–6	–3.8	–2.9	–2.2
$\Delta F_{(\mathrm{u})}$ (GHz)	1.45	1.25	1.1	1.0	0.21
$\Delta F_{(\mathrm{n\text{-}u})}$ (GHz)	1.7	1.45	1.2	0.45	0.19
$\delta \Delta F$ (%)	–15	–14	–8	122	11
$D_{(\mathrm{u})}$	0.667	1.088	1.848	3.3	1.373
$D_{(\mathrm{n\text{-}u})}$	0.884	1.334	2.1	1.53	1.271
δD (%)	–25	–18	–12	117	8

Delay time of the MMDL can also be increased almost proportionally by increasing the length of the meander strips $2A$ (Table II). However, the bandwidth of the MMDL almost proportionally becomes narrower in such cases. For example, increasing four times the length of the meander strips $2A$ (from 10 mm to 40 mm) the delay time of the uniform impedance MMDL increases 3.5 times, but at the same bandwidth narrowed to about 3.6 times. Increasing the length of the meander strips $2A$ difference between delay time of uniform impedance MMDL and delay time of non-uniform impedance MMDL diminishes. That is, when the inhomogeneity of the MMDL in the longitudinal direction is reduced (according to Fig. 1 and Fig. 2 – along the x axis). It is also seen in Table II that the bandwidth of the uniform impedance MMDL is in most cases twice and more times wider than the bandwidth of the non-uniform impedance MMDL. Only when the length of the strips becomes lager (in this case $2A = 40$ mm or $2A/h = 80$), the bandwidths of the uniform and non-uniform impedance MMDLs become equal. D-factor of the uniform impedance MMDL is also twice better than that of the non-uniform impedance MMDL (except for the mentioned case, where $2A/h = 80$).

TABLE II. DEPENDENCE OF CHARACTERISTICS OF THE MMDL ON LENGTH OF THE MEANDER STRIPS AT $\varepsilon_r = 9.6$, $h = 0.5$ mm, $N = 20$.

Characteristic of the MMDL	**Length of the meander strips, 2*A* (mm)**		
	10	20	40
$t_{d(u)}$ (ns)	1.8	3.3	6.3
$t_{d(n\text{-}u)}$ (ns)	1.89	3.4	6.4
δt_d (%)	–4.5	–2.9	–2
$\Delta F_{(u)}$ (GHz)	2.0	1.0	0.55
$\Delta F_{(n\text{-}u)}$ (GHz)	0.7	0.45	0.55
$\delta \Delta F$ (%)	186	122	0
$D_{(u)}$	3.6	3.3	3.465
$D_{(n\text{-}u)}$	1.323	1.53	3.52
δD (%)	172	117	–1.6

Delay time of the MMDL can be increased, without increasing its size, by adopting the dielectric substrate with a higher permittivity. This approach is illustrated by the characteristics and parameters in Table III. It is noteworthy that the increase of the substrate permittivity of approximately 70% (16/9.6 ≅ 1.7), leaving the other design parameters constant, increases the delay time by 25% only (4.12/3.3 ≅ 1.24), whereas the bandwidth narrows by four times (1.0/0.25 = 4.0). Some characteristics of the uniform impedance MMDL are changing in a less degree to the positive way, than the same characteristics of the non-uniform impedance MMDL. E.g. increasing the permittivity of the substrate, as in the earlier example, by 70%, the *D*-factor of the uniform impedance MMDL just barely increases by 5% (3.465/3.3 ≅ 1.05), and the *D*-factor of the non-uniform impedance MMDL increases more than two times (3.52/1.53 ≅ 2.3).

TABLE III. DEPENDENCE OF CHARACTERISTICS OF THE MMDL ON PERMITTIVITY OF THE DIELECTRIC SUBSTRATE AT $h = 0.5$ mm, $2A = 20$ mm, $N = 20$.

Characteristic of the MMDL	**Permittivity of dielectric substrate, ε_r**		
	4.5	9.6	16
$t_{d(u)}$ (ns)	2.5	3.3	4.12
$t_{d(n\text{-}u)}$ (ns)	2.59	3.4	4.2
δt_d (%)	–3.3	–2.9	–1.9
$\Delta F_{(u)}$ (GHz)	1.3	1.0	0.25
$\Delta F_{(n\text{-}u)}$ (GHz)	1.35	0.45	0.25
$\delta \Delta F$ (%)	–3.7	122	0
$D_{(u)}$	3. 25	3.3	1.03
$D_{(n\text{-}u)}$	3.497	1.53	1.05
δD (%)	–7.0	117	–1.9

The bandwidth of the MMDL can be increased without reducing its delay time by increasing the space *S* between meander strips. Variation of the MMDL characteristics according to several space changes is shown in Table IV. Variation of space between the strips is very effective means of influence on the MMDL characteristics, e.g. increasing the space to 4 times (1.0/0.25 = 4) causes the expansion of the bandwidth more than 4 times (1.15/0.25 = 4.6). It should be noted also that the characteristics of the uniform impedance MMDL are less sensitive to changes of the space than the characteristics of the non-uniform impedance MMDL. For example, increasing the space four times (2.0/0.25 = 4.0) leads to increase of the *D*-factor of the uniform impedance MMDL by 3.916/0.933 ≅ 4.2 times, and the *D*-factor of the non-uniform impedance MMDL in this case is improved 4.152/0.815 ≅ 5.09 times (it means that in the example shown, the uniform impedance MMDL 20% less sensitive than the non-uniform one).

TABLE IV. DEPENDENCE OF CHARACTERISTICS OF THE MMDL ON SPACE BETWEEN MEANDER STRIPS AT $\varepsilon_r = 9.6$, $h = 0.5$ mm, $2A = 20$ mm, $N = 20$.

Characteristic of the MMDL	**Space between meander strips, *S* (mm)**			
	0.25	0.5	1.0	2.0
$t_{d(u)}$ (ns)	3.11	3.3	3.56	3.78
$t_{d(n\text{-}u)}$ (ns)	3.26	3.4	3.61	3.79
δt_d (%)	–4.4	–2.9	–1.4	–0.33
$\Delta F_{(u)}$ (GHz)	0.3	1.0	1.1	1.25
$\Delta F_{(n\text{-}u)}$ (GHz)	0.25	0.45	1.15	1.3
$\delta \Delta F$ (%)	20	122	–4.3	–3.8
$D_{(u)}$	0.933	3.3	3.916	4.725
$D_{(n\text{-}u)}$	0.815	1.53	4.152	4.927
δD (%)	14	117	–5.7	–4.1

III. THE INFLUENCE OF PHASE VELOCITY DIFFERENCES ON FREQUENCY CHARACTERISTICS OF THE MMDL

In general, *N* modes can propagate in the MCML which consists of *N* signal conductors [21]. However, only the even and odd modes are practically interesting when the MCML model is used for the design of the MMDL. The odd mode is used for analysis of the MMDL at high frequencies beyond the bandwidth, when the phase difference between adjacent meander strips voltages is equal to $(2k + 1)\pi$, where $k = 0, 1, 2, \ldots$. Therefore, when designing the MMDL, determination of the size of the meander topology and parameters of the dielectric substrate, it is sufficient to calculate the MCML parameters for the even mode only. The even mode is possible in the MCML when phase velocities of electro-magnetic waves propagating along the equipotential conductors of the MCML are equal, which in turn is only possible if the effective permittivities of the conductors are equal for the even mode. In case of periodic and infinite MCMLs this condition is satisfied naturally. In the MCMLs consisting of a finite number of conductors effective permeability is very irregular (Fig. 5). This irregular distribution of permittivity affects the determination of the delay time and the bandwidth of the designed MMDL (Fig. 6).

Side conductors of the MCML should be wider than the inner ones in order to make its effective permittivity equal in all strips (i.e. to ensure the operation of even mode) [19]. However, characteristic impedance of such wide conductors differs significantly from the impedance of the regular part of the MCML as well as the rest of the signal transmission path, resulting in mismatch of the MMDL. For this reason, in addition to the resonances which have been described by (1), the significant oscillations of amplitude greater than 3 dB appear in the magnitude response of S21 parameter of this MMDL (Fig. 6(a)).

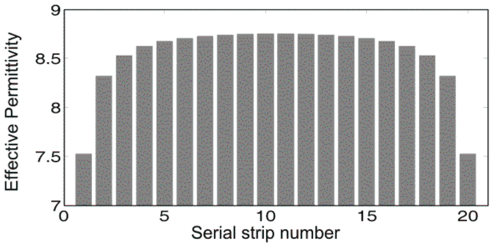

Fig. 5. Non-uniform effective permittivity of the MMDL designed on the periodic multiconductor microstrip line basis at $\varepsilon_r = 9.6$, $h = 0.5$ mm, $W = 0.6$ mm, $S = 0.5$ mm, $2A = 20$ mm, $N = 20$.

Phase distortion of the MMDL designed according to the even mode MCML model, is less than the phase distortion of the MMDL based on the multi-mode MCML (Fig. 6(b)). However, oscillations of magnitude response of S21 parameter lead to the fact that the bandwidth of the uniform effective permittivity MMDL is determined by the amplitude response rather than phase one, how it was investigating the influence of characteristic impedance non-uniformity on frequency characteristics of the MMDL (see Chapter II of this paper).

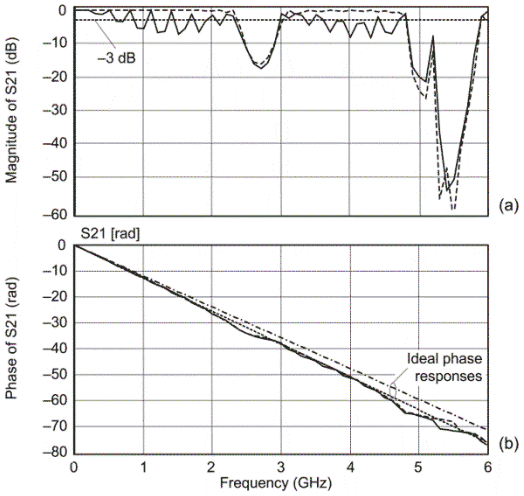

Fig. 6. Magnitude (a) and argument (b) response of parameter S21 of the MMDL which design parameters are following: $\varepsilon_r = 9.6$, $h = 0.5$ mm, $2A = 20$ mm, $N = 10$. Solid curves correspond to the MMDL of uniform effective permittivity, and dashed ones correspond to the MMDL of non-uniform effective permittivity.

The results of the simulation of the MMDLs based on the model of the MCML, operating in the even mode are shown in Tables V–VIII with characteristics marked the subscript (u), which corresponds to the uniform effective permittivity MMDL. Characteristics of the MMDL based on the periodic MCML model, operating in the mixed modes are shown for comparison in the same tables; the subscript (n-u) marks these characteristics, i.e. the non-uniform effective permittivity MMDL. Analysis of the characteristics presented in Tables V–VIII, shows that delay time of the uniform effective permittivity MMDL due to the greater width of the side meander strips in all investigated cases is larger than delay of the non-uniform effective permittivity MMDL. At the same time bandwidth $\Delta F_{(u)}$ of the uniform effective permittivity MMDL, due to the significant characteristic impedance mismatch in most cases studied is narrower than bandwidth $\Delta F_{(u-n)}$ of the non-uniform effective permittivity MMDL.

TABLE V. DEPENDENCE OF CHARACTERISTICS OF THE MMDL ON NUMBER OF THE MEANDER STRIPS AT $\varepsilon_r = 9.6$, $h = 0.5$ mm, $2A = 20$ mm.

Characteristic of the MMDL	**Number of meander strips, *N***			
	3	5	10	20
$t_{d(u)}$ (ns)	0.706	1.05	2.01	3.64
$t_{d(n-u)}$ (ns)	0.642	0.948	1.88	3.42
δt_d (%)	10	11	6.9	6.4
$\Delta F_{(u)}$ (GHz)	1.1	0.63	0.5	0.5
$\Delta F_{(n-u)}$ (GHz)	1.5	1.2	0.91	0.6
$\delta \Delta F$ (%)	–27	–48	–45	–17
$D_{(u)}$	0.777	0.662	1.005	1.82
$D_{(n-u)}$	0.963	1.138	1.71	2.052
δD (%)	–19	–42	–41	–11

Increasing the number of meander strips correspondingly increases delay time of the MMDL (Table V). However, due to narrow bandwidth of the uniform effective permittivity MMDLs their *D*-factor is up to 42% less than the *D*-factor of the non-uniform effective permittivity MMDLs. Only at the largest of the investigated number of meander strips ($N = 20$) this difference was rather negligible – 11%.

Delay time of the MMDL can be changed also by varying the length of the meander strips (Table VI) and adopting dielectric constant of the substrate (Table VII).

TABLE VI. DEPENDENCE OF CHARACTERISTICS OF THE MMDL ON LENGTH OF THE MEANDER STRIPS AT $\varepsilon_r = 9.6$, $h = 0.5$ mm, $N = 20$.

Characteristic of the MMDL	**Length of the meander strips, 2*A* (mm)**		
	10	20	40
$t_{d(u)}$ (ns)	2.12	3.64	6.91
$t_{d(n-u)}$ (ns)	2.04	3.42	6.63
δt_d (%)	3.9	6.4	4.2
$\Delta F_{(u)}$ (GHz)	1.0	0.5	0.3
$\Delta F_{(n-u)}$ (GHz)	1.3	0.6	0.3
$\delta \Delta F$ (%)	–23	–17	0
$D_{(u)}$	2.12	1.82	2.073
$D_{(n-u)}$	2.652	2.052	1.989
δD (%)	–20	–11	4.2

The performed calculations have shown that varying the length of the meander strips 2*A* and permittivity of the substrate ε_r, characteristics of the MMDLs change in a similar way; i.e. increasing 2*A* or ε_r, the delay time increases also, however, the bandwidth becomes narrower. Again it was found that the bandwidth of the uniform effective permittivity MMDL in most cases is narrower than the bandwidth of the non-uniform effective permittivity MMDL. Only at $2A = 40$ mm (Table VI) and $\varepsilon_r = 16$ (Table VII), the bandwidth of both lines: of the uniform and non-uniform effective permittivity MMDL, is the same. *D*-factor of the investigated MMDLs varying 2*A* and ε_r has changed similarly.

TABLE VII. DEPENDENCE OF CHARACTERISTICS OF THE MMDL ON PERMITTIVITY OF THE DIELECTRIC SUBSTRATE AT $h = 0.5$ mm, $2A = 20$ mm, $N = 20$.

Characteristic of the MMDL	**Permittivity of dielectric substrate, ε_r**		
	4.5	9.6	16
$t_{d(u)}$ (ns)	2.62	3.64	5.1
$t_{d(n-u)}$ (ns)	2.61	3.42	4.78
δt_d (%)	0.38	6.4	6.7
$\Delta F_{(u)}$ (GHz)	1.5	0.5	0.3
$\Delta F_{(n-u)}$ (GHz)	1.6	0,6	0.3
$\delta \Delta F$ (%)	–6.3	–17	0
$D_{(u)}$	3.93	1.82	1.53
$D_{(n-u)}$	4.176	2.052	1.434
δD (%)	–5.9	–11	6.7

The influence of the distance between the meander strips on the characteristics of the MMDL line is shown in Table VIII. Increasing this space the bandwidth of the MMDL increases proportionally and delay time remains almost unchanged. As in previous cases (Tables V–VII) bandwidth and *D*-factor of the uniform effective permittivity MMDL is lower than the same characteristics of the non-uniform effective permittivity MMDL. Only at a relatively large space between the strips ($S = 2.0$ mm) the uniform effective permittivity MMDL has better characteristics.

TABLE VIII. DEPENDENCE OF CHARACTERISTICS OF THE MMDL ON SPACE BETWEEN MEANDER STRIPS AT $\varepsilon_r = 9.6$, $h = 0.5$ mm, $2A = 20$ mm, $N = 20$.

Characteristic of the MMDL	**Space between meander strips, *S* (mm)**		
	0.5	1.0	2.0
$t_{d(u)}$ (ns)	3.76	3.64	3.99
$t_{d(n-u)}$ (ns)	3.11	3.42	3.96
δt_d (%)	21	6.4	0.76
$\Delta F_{(u)}$ (GHz)	0.2	0.5	1.1
$\Delta F_{(n-u)}$ (GHz)	0.6	0.6	1.0
$\delta \Delta F$ (%)	–67	–17	10
$D_{(u)}$	0.752	1.82	4.389
$D_{(n-u)}$	1.866	2.052	3.96
δD (%)	–60	–11	11

IV. CONCLUSIONS

The influence of non-uniformity of the multiconductor microstrip line (MCML) parameters: characteristic impedance and effective permittivity on characteristics of the meander microstrip delay line (MMDL): delay time and bandwidth is studied in this paper. Many calculations those simulate the design of the MMDL with different size of topology and various permittivity of the dielectric substrate were made.

The performed calculations showed that the MMDL based on the model of the uniform impedance MCML is better matched with the transmission path and has a wider bandwidth than the non-uniform impedance MMDL. However, delay time of the uniform impedance MMDL due to the fact that the electromagnetic wave propagates in them faster is always slightly less than the delay of the non-uniform impedance MMDL.

Alignment of effective permittivity of the MMDL is performed by widening the meander side strips, so the delay time of the uniform permittivity MMDL is always higher, and it was found that phase distortion is less than in the non-uniform permittivity MMDL case. However, matching of uniform permittivity MMDLs with the transmission path is worse and bandwidth is narrower than non-uniform permittivity MMDLs.

The possibility to analyse the responses of the MMDLs in which both the characteristic impedance and the effective permittivity are uniform is currently considered.

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REFERENCES

[1] Y. Horii, S. Gupta, B. Nikfal, C. Caloz, “Multilayer broadside-coupled dispersive delay structures for analog signal processing”, *IEEE Microwave and Wireless Components Letters*, vol. 22, no. 1, pp. 1–3, Jan. 2012. [Online]. Available: http://dx.doi.org/10.1109/LMWC.2011.2176476

[2] B. Xiang, A. Kopa, Z. Fu, A. B. Apsel, “Theoretical analysis and practical considerations for the integrated time-stretching system using dispersive delay line (DDL)”, *Transactions on MTT, IEEE*, vol. 60, pp. 3449–3457, Nov. 2012. [Online]. Available: http://dx.doi.org/10.1109/TMTT.2012.2215623

[3] G. Li, Y. M. Tousi, A. Hassibi, E. Afshari, “Delay line based analog-to-digital converters”, *IEEE Transactions on Circuits and Systems-II. Express Briefs*, vol. 56, pp. 464–468, Jun. 2009.

[4] H. Hsu, J. H. Wen, “Timing synchronization in ultra-wideband systems with delay line combination receivers”, *Communications Letters, IEEE*, vol. 11, pp. 264–266, Mar. 2007. [Online]. Available: http://dx.doi.org/10.1109/LCOMM.2007.061765

[5] A. L. Amadjikpè, D. Choudhury, C. E. Patterson, B. Lacroix, G. E. Ponchak, John Papapolymerou, “Integrated 60-GHz antenna on multilayer organic package with broadside and end-fire radiation”, *IEEE Transactions on MTT,* vol. 61, pp. 303–315, Jan. 2013. [Online]. Available: http://dx.doi.org/10.1109/TMTT.2012.2226598

[6] S. Park, S. Jeon, “A 15–40 GHz CMOS true-time delay circuit for UWB multi-antenna systems”, *IEEE Microwave and Wireless Components Letters,* vol. 23, pp. 149–151, Mar. 2013. [Online]. Available: http://dx.doi.org/10.1109/LMWC.2013.2244872

[7] R. Levy, “Realization of practical lumped element all-pass networks for delay equalizationof RF and microwave filters”, *IEEE Transactions on MTT,* vol. 59, pp. 3307–3311, Dec. 2011 [Online]. Available: http://dx.doi.org/10.1109/TMTT.2011.2172809

[8] V. Daskevicius, J. Skudutis, A. Katkevicius, S. Staras, “Simulation and properties of the wide-band hybrid slow-wave system”, *Elektronika ir elektrotechnika (Electronics and Electrical Engineering)*, no. 8, pp. 43–46, 2010.

[9] H. Kim, F. Bien, Y. Hur, S. Chandramouh, J. Cha, E. Gebara, J. Laskar, “A 0.25-um BiCMOS feed forward equalizer using active delay line for backplane communication”, in *Proc. of IEEE International Symposium on Circuits and Systems (ISCAS 2007)*, New Orleans, 2007, pp. 193–196. [Online]. Available: http://dx.doi.org/10.1109/ISCAS.2007.378309

[10] V. Urbanavicius, A. Gurskas, R. Martavicius, “Simulation of the meander delay line using the hybrid method”, *Elektronika ir elektrotechnika (Electronics and Electrical Engineering)*, no. 2, pp. 6–9, 2009.

[11] W.-T. Li, Y.-C. Chiang, J.-H. Tsai, H.-Y. Yang, J.-H. Cheng, T.-W. Huang, “60-GHz 5-bit phase shifter with integrated VGA phase-error compensation”, *IEEE Transactions on MTT,* vol. 61, pp. 1224–1235, Mar. 2013. [Online]. Available: http://dx.doi.org/10.1109/TMTT.2013.2244226

[12] S. Staras, A. Katkevicius, “Properties of helical structures containing periodical inhomogeneities”, *Elektronika ir elektrotechnika (Electronics and Electrical Engineering)*, no. 3, pp. 49–52, 2010.

[13] O. Jagutzki, V. Dangendorf, R. Lauckb, A. Czascha, J. Milnesc, “A position- and time-sensitive photon-counting detector with delayline read-out”, in *Proc. of SPIE Conference Optics and Optoelectronics*, Prague, 2007, pp. 1–11.

[14] A. Katkevicius, V. Malisauskas, D. Plonis, A. Serackis, “Calculations of characteristics of microwave devices using artificial neural networks”, *Przegląd elektrotechniczny (Electrical Review)*, vol. 88 no. 1a, pp. 281–285, Jan. 2012.

[15] S. Staras, R. Martavicius, J. Skudutis, V. Urbanavicius, V. Daskevicius, *Wide-Band Slow-Wave Systems: Simulation and Applications*, Boca Raton: CRC Press, 2012.

[16] R. Pomarnacki, A. Gurskas, V. Urbanavicius, “Topology synthesis of the multi-tapped meander delay line using Monte Carlo method”, *Elektronika ir elektrotechnika (Electronics and Electrical Engineering)*, vol. 18, no. 8, pp. 41–44, 2012.

[17] E. Metlevskis, V. Urbanavicius, “Analysis of charge distribution on rectangular microstrip structures”, *Acta Physica Polonica A*, vol. 119, pp. 503–508, Feb. 2011.

[18] R. Pomarnacki, A. Krukonis, “Parallel synthesis of multiconductor microstrip lines”, *Science – Future of Lithuania*, vol. 3, no. 1, pp. 104–109, Jan. 2011. (in Lithuanian).

[19] S. Mikucionis, V. Urbanavicius, “Synthesis of six-conductors symmetrically coupled microstrip line, operating in a normal mode”, *Elektronika ir elektrotechnika (Electronics and Electrical Engineering)*, no. 4, pp. 47–52, Apr. 2011.

[20] S. Haykin, B. V. Veen, *Signals and Systems*. John Wiley & Sons, Inc, 2003, pp. 263–264.

[21] C. R. Paul, *Analysis of Multiconductor Transmission Lines*. New York: IEEE Press, Wiley-Interscience, 2008, pp. 89–102.