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SYNTHESIS OF MULTICONDUCTOR MICROSTRIP LINES OPERATING IN NORMAL MODES

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Abstract. The article presents a synthesis technique for a symmetrically coupled multiconductor microstrip line operating in normal modes and looks at the examples of the synthesis of a ten-conductor symmetrically coupled multiconductor microstrip line operating in even- and odd normal modes. The paper investigates the dependences of the parameters of the introduced lines.

Keywords: multiconductor microstrip line, method of moments, normal wave, normal mode, multiconductor line synthesis, modal voltage.

Introduction

A symmetrically coupled multiconductor microstrip line (MCML) consists of a dielectric substrate of infinite length and width with a conducting layer on the one side of the substrate and microstrip conductors on the other (Fig. 1). The number of conductors, their width and space between them is specified independently. Due to their planar design, the lines are widely used in many microwave devices, for example, (Kralicek, Sabath 1997; Yordanov *et al.* 2007; Han *et al.* 2009). MCMLs are also used as physical models for the analysis and design of various microwave devices, for example, meander and helical retard and deflecting systems (Burokas, Štaras 2008; Daškevičius *et al.* 2010; Štaras 2005; Daškevičius *et al.* 2009; Urbanavičius *et al.* 2009, 2007), meander delay lines (Gurskas *et al.* 2010; Cheldavi 2003; Konoplev *et al.* 2005; Štaras, Katkevičius 2010), waveguides (Mališauskas, Plonis 2010).

It is generally known that in a lossless MCML consisting of N conductors, N normal modes (or normal waves) can be propagated (Tripathi, Lee 1989). MCMLs are characterized by N effective dielectric permittivities and characteristic impedances Zki, where *k* is the type of a normal mode and *i* is the conductor number.

Under non-modal (or multimodal) propagation, phase velocities in different conductors differ from each other in the MCML as a result of the superposition of the propagating modes. The transverse structure of the electric and magnetic fields of the transmitted waves is not retained along the MCML. Therefore, microwave devices that use MCML models should be designed so that only a single normal mode could be propagated (Mansur 2001).

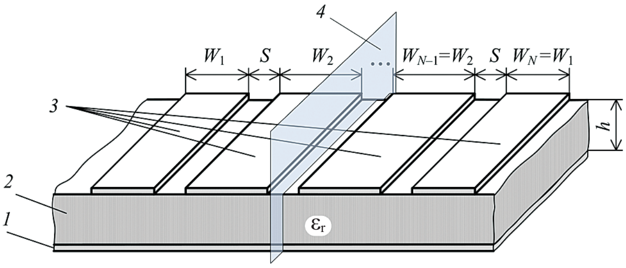

Fig. 1. The generalized structure of the symmetrically coupled multiconductor microstrip line: *1* – reference conductor; *2* – dielectric substrate; *3* – microstrip conductors; *4* – plane of symmetry

The synthesis of an electronic device is a procedure of finding its constructive dimensions according to the given electric characteristics of the device. Synthesis problems are of particular interest for creating CAD systems for microwave devices, and therefore many researches were intensively solving them in the past decade (Rawat, Ghannouchi 2009; Chiang *et al.* 2009; Yioultsis *et al.* 2003; Lee, Tsai 2009). In case of the MCML operating in a normal mode, synthesis is an iterative process of finding topological dimensions of an MCML, which restricts propagation to a single normal mode in the line when specified modal voltages are applied.

A survey on literature reveals that there is no well-established systematic design technique for the synthesis of MCMLs operating in a normal mode. In the absence of such technique, devices are typically designed using extensive software simulations where high-frequency simulators (mostly commercial) are used for determining the required design parameters for a good coverage (Rawat, Ghannouchi 2009; Chiang *et al.* 2009; Yioultsis *et al.* 2003).

This paper proposes a synthesis technique for the MCML operating in a normal mode. This technique exhibits rather fast computational efficiency and good accuracy. The accuracy of the mathematical model of the MCML has been checked to be correct in earlier works (Mikučionis, Urbanavičius 2011).

Synthesis Algorithm

The proposed synthesis algorithm for a symmetrically coupled MCML is based on the iteration of calculating modal voltages and changing microstrip conductor widths and spaces between them in order to find such structure of the MCML, for which the amplitudes of modal voltages are equal for every microstrip conductor.

Modal voltages of the line are calculated by finding the eigenvalues of a relative effective dielectric permittivity vector solving an eigenvalue equation

$$\left[\mathrm{C}_1\right]\left[\mathrm{V}\right]=\left[\mathrm{C}_1^{(\mathrm{a})}\right]\left[\mathrm{V}\right]\left[\varepsilon_{\mathrm{reff}}\right], \tag{1}$$

where $\left[\mathrm{C}_1\right]$ is the matrix of the partial capacitances of the MCML; $\left[\mathrm{C}_1^{(\mathrm{a})}\right]$ is a similar matrix of the same MCML with free space in the place of dielectric substrate; $\left[\varepsilon_{\mathrm{reff}}\right]$ is the vector of relative effective dielectric permittivity; $\left[\mathrm{V}\right]$ is the matrix consisting of modal voltage vectors.

The analysis of the MCML can be carried out using various methods, e. g. finite difference (Pomarnacki *et al.* 2010), partial areas (Nickelson *et al.* 2009). We propose to use the combination of the method of moments and partial images technique (Gurskas *et al.* 2010; Mikučionis, Urbanavičius 2010a; Metlevskis, Urbanavičius 2011) for an accurate calculation of partial capacitance matrices $\left[\mathrm{C}_1\right]$ and $\left[\mathrm{C}_1^{(\mathrm{a})}\right]$.

In general case, modal voltages of a multiconductor microstrip line can be expressed as the functions of the widths of conductors:

$$V_i = f_i\left(W_1, W_2, \ldots W_N\right), \tag{2}$$

where i is the number of the conductor; V_i is the modal voltage of the i-th conductor; W_k is the width of the k-th conductor.

The earlier calculations (Mikučionis, Urbanavičius 2010a, 2010b) revealed that in order to obtain normal modes when the voltages of the same amplitude are applied to the conductors, the lines had to be symmetric, i.e., $W_1 = W_N$, $W_2 = W_{N-1}$ etc. Furthermore, modal voltages of symmetric conductors are also symmetric, i. e., $V_1 = V_N$, $V_2 = V_{N-1}$ etc. Therefore, Eq. (2) can be reduced and simplified to:

$$V_i = f_i\left(W_1, W_2, \ldots, W_{N/2}\right). \tag{3}$$

The aim of synthesis is to find such $W_1, \ldots, W_N$ values, so that the difference between the modal voltages of the conductors would be less than or equal to the desired error ΔV. It was chosen to leave the width of the fixed central conductors, and to change the values of all other in order to obtain the desired modal voltages. It is also convenient to normalize voltages by the voltage of one of the conductors for better control of the difference between voltages. The voltage of any of the conductors could be chosen. For the sake of simplicity in the proposed technique, the procedure of normalizing all voltages by V_1 was adopted. In order to find the needed widths of the conductors, the following inequality system must be solved:

$$\begin{cases} \left\| V_1 \right| - \left| V_2 \right\| = f\left(W_1, \ldots, W_N\right) < \Delta V; \\ \left\| V_1 \right| - \left| V_3 \right\| = f\left(W_1, \ldots, W_N\right) < \Delta V; \\ \ldots \\ \left\| V_1 \right| - \left| V_{N/2} \right\| = f\left(W_1, \ldots, W_N\right) < \Delta V. \end{cases} \tag{4}$$

It has been also noticed that the modal voltage of the conductor strongly depends on its own width, and dependence on the width of other conductor is quite weak (Mikučionis, Urbanavičius 2010a, 2010b, 2011). Therefore, the above inequality system (4) can be modified to:

$$\begin{cases} \left\| V_1 \right| - \left| V_2 \right\| = f\left(W_2\right) < \Delta V; \\ \left\| V_1 \right| - \left| V_3 \right\| = f\left(W_3\right) < \Delta V; \\ \ldots \\ \left\| V_1 \right| - \left| V_{N/2} \right\| = f\left(W_{N/2}\right) < \Delta V. \end{cases} \tag{4a}$$

Any numerical root finding technique can be used for finding the widths of the conductors by alternating between inequalities until those are satisfied.

The secant method was chosen by the author because of its suitability for numerical techniques and good convergence. Recurrence relation for the secant method is:

$$x_n = x_{n-1} - f\left(x_{n-1}\right)\frac{x_{n-1} - x_{n-2}}{f\left(x_{n-1}\right) - f\left(x_{n-2}\right)}, \tag{5}$$

where x_n is the "newest" calculated value of W_i; x_{n-1} is the value of W_i calculated on the previous calculation cycle; x_{n-2} is the value of W_i calculated on the pre-previous calculation cycles; $f\left(x_{n-1}\right)$ is the value of voltage difference calculated on the previous calculation cycle; $f\left(x_{n-2}\right)$ is the value of voltage difference calculated on the pre-previous calculation cycle.

The flowchart of the synthesis algorithm of the symmetrically coupled MCML operating in a normal mode is presented in Fig. 2.

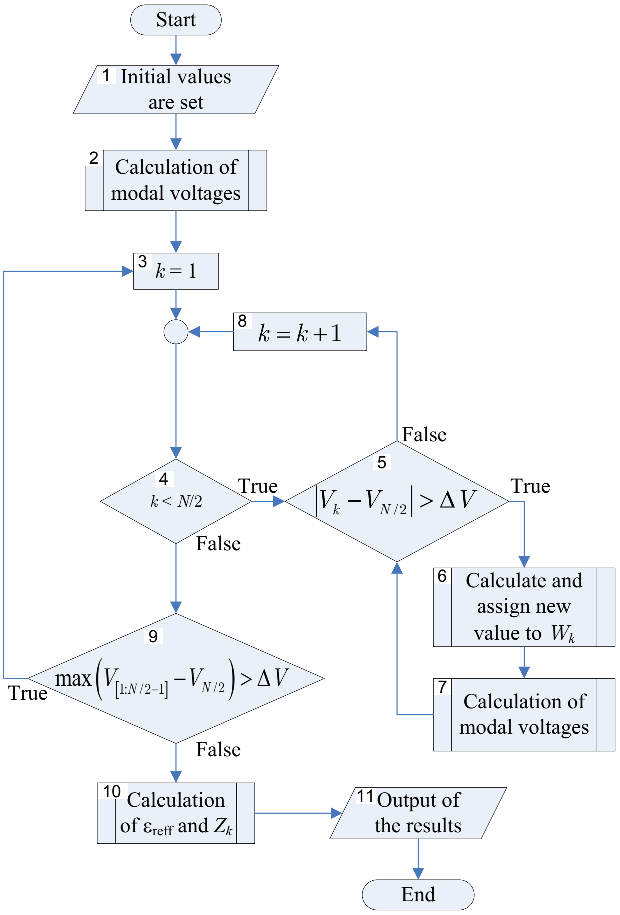

Fig. 2. Flowchart of the synthesis algorithm

The synthesis algorithm consists of 11 steps:

1. Initial values needed for calculation are set: the thickness of dielectric substrate h, relative dielectric permittivity of dielectric substrate ε_r, initial conductor widths W_i, gap size between conductors S and desired voltage error ΔV.
2. Modal voltages are calculated according to Eq. (1).
3. The number of conductor k is assigned to 1.
4. Checking if the number of the conductor is less than a half of the total number of the conductors of the MCML; in case it is true, Step 5 is processed, otherwise, go to Step 9.
5. Checking if the voltage of the k-th conductor differs from that of the central conductor(s) by more than ΔV; in case it is true, proceed to Step 6, otherwise, proceed to the next conductor (Step 8).
6. A new value of W_k is calculated according to Eq. (5).
7. Modal voltages are calculated according to Eq. (1).
8. Calculation steps to the next conductor (index k is incremented by one).
9. Checking if the highest difference between the voltages of the conductors and the voltage of the reference conductor is more than chosen ΔV, in case it is true, calculation is repeated from Step 3, otherwise, proceed to Step 10.
10. The characteristic impedances of the conductors and relative effective permittivity are calculated according to the capacitances of the conductors.
11. The results are output.

Investigation into the Proposed Technique

The dependence of conductor width W_i, effective relative permittivity $\varepsilon_{\text{reff}}$ and characteristic impedance Z_i on the constructive parameters of the MCML (S, h and ε_r) was investigated.

The proposed technique was used for synthesizing a ten-conductor MCML operating in even and odd normal modes in order to investigate the dependence of MCML characteristics on its constructive parameters (S and W_i). These modes were selected due to their potential practical utility, thus applying to the conductors correspondently equal voltages +1 V,…, +1 V or counter-phase voltages +1 V, –1 V,…, +1 V, –1 V respectfully. The widths of the conductors that ensured the propagation of a single normal mode were searched during the synthesis procedure, accordingly to the defined S/h ratio, the permittivity of dielectric substrate ε_r and the selected type of a normal mode. After finding such widths, the process of synthesis was finished, and the characteristic impedance $Z_{je,o}$ of the conductors of the MCML and relative effective permittivity $\varepsilon_{\text{reffe,o}}$ were calculated. The results of the synthesis of the MCML operating in even and odd normal modes are shown in Figs. 3–8.

In order to ensure even normal mode propagation in the MCML, the width of external conductors should be greater than that of the internal ones (Fig. 3). In case of an odd normal wave (Fig. 4), a contrary situation occurs –external conductors should be narrower than the internal ones.

The analysis of the curves presented in Fig. 3 for the even mode and in Fig. 4 for the odd mode shows that the widths of external conductors have the major influence on the propagation of normal modes in the MCML, while the widths of internal conductors vary negligibly while changing S/h.

The diagrams presented in Figs. 5 and 6 show that relative effective dielectric permittivity $\varepsilon_{\text{reffe,o}}$ changes slightly while varying the space between conductors after S/h is larger or equal to 4. Effective dielectric permittivity slightly diminishes at increasing gaps between the conductors in case of an even mode and increases in case of an odd mode.

An increase in the gap between the adjacent conductors of the MCML causes their characteristic impedances

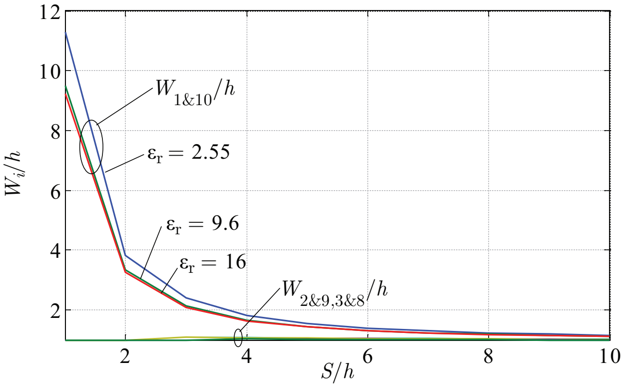

Fig. 3. The dependence of the width of the conductors of the MCML operating in an even mode on the gap size between them and the relative permittivity of the dielectric substrate

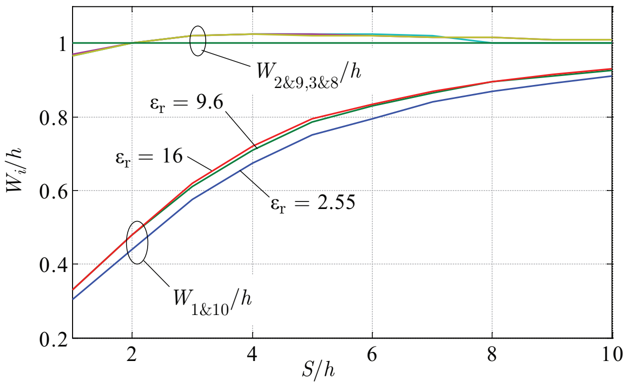

Fig. 4. The dependence of the width of the conductors of the MCML operating in an odd mode on the gap size between them and the relative permittivity of the dielectric substrate

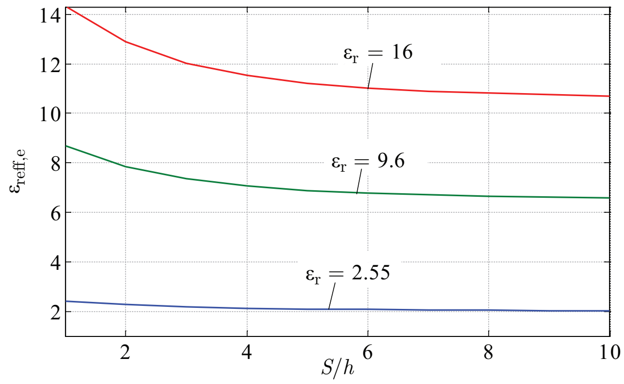

Fig. 5. The dependence of effective relative dielectric permittivity on the gap size between the conductors and the relative permittivity of the dielectric substrate of the MCML operating in an even mode

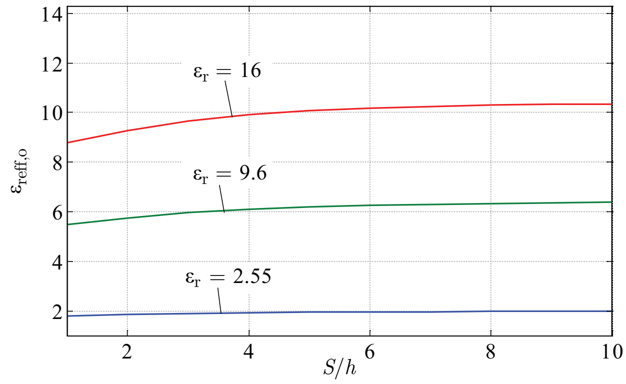

Fig. 6. The dependence of effective relative dielectric permittivity on the gap size between the conductors and the relative permittivity of the substrate of the MCML operating in an odd mode

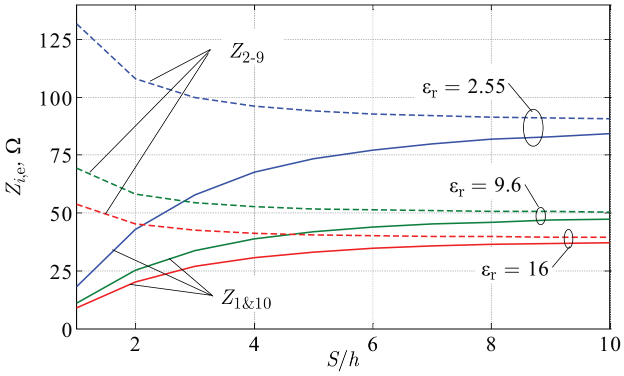

Fig. 7. The dependence of the characteristic impedance of the conductors of the MCML operating in an even mode on the gap size between them and the relative permittivity of the dielectric substrate

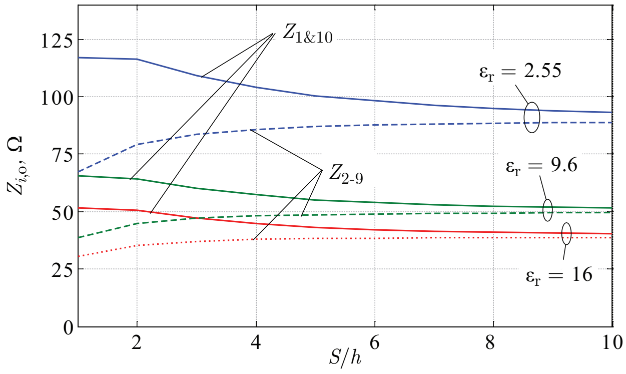

Fig. 8. The dependence of the characteristic impedance of the conductors of the MCML operating in an odd mode on the gap size between them and the relative dielectric permittivity of the substrate

to become approximately equal. The difference between MCMLs operating in both normal modes becomes negligible (Figs. 7 and 8). Such dependence can be explained by diminishing the interaction between the conductors when the distance between them increases.

The conductors of the synthesized MCML were divided into 2 000–5 000 sub-areas depending on initial conditions, and the synthesis procedure of a single MCML took 2–12 minutes (Pentium 4 CPU, 3 GHz clock frequency and 1 GB RAM).

Conclusions

The article has discussed a fast and accurate synthesis technique of the symmetrically coupled multiconductor microstrip line (MCML) operating in a normal mode. In order to demonstrate the feasibility of the proposed techniques, the author has applied specific software and synthesized as well as investigated several MCMLs operating in even- and odd normal modes. It has been found that due to an increase in the space between adjacent conductors, the MCML becomes similar to the set of uncoupled microstrips with equal impedance regardless of the operating mode. It has also been discovered that external conductors have the major impact on a normal mode in the symmetrically coupled MCML. The conductors of the synthesized MCML were divided into 2 000–5 000 sub-areas (for odd- and even-modes respectively) during all calculations and the synthesis procedure took 2–12 minutes (Pentium 4 CPU, 3 GHz clock frequency and 1 GB RAM).

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DAUGIALAIDĖS MIKROJUOSTELINĖS LINIJOS, VEIKIANČIOS NORMALIŲJŲ BANGŲ REŽIMU, SINTEZĖ

Š. Mikučionis

Santrauka

Straipsnyje išnagrinėtas simetrinių daugialaidžių mikrojuostelinių linijų, veikiančių normaliųjų bangų režimu, sintezės algoritmas. Kaip pavyzdys pateikti dešimties laidininkų simetrinės daugialaidės mikrojuostelinės linijos, veikiančios lyginės ir nelyginės bangų režimu, sintezės rezultatai, aprašyti linijos parametrai.

Reikšminiai žodžiai: daugialaidė mikrojuostelinė linija, momentų metodas, normalioji banga, daugialaidžių linijų sintezė, modalinė įtampa.