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AUKŠTŲJŲ DAŽNIŲ TECHNOLOGIJA, MIKROBANGOS

Simulation of the Axially Symmetrical Helical Line

V. Daškevičius, J. Skudutis

Department of Computer Engineering, Vilnius Gediminas Technical University,
Naugarduko str. 41, LT-03227, phone: +370 5 2744767; e-mail: julius.skudutis@el.vgtu.lt

S. Štaras

Department of Electronic Systems, Vilnius Gediminas Technical University,
Naugarduko str. 41, LT-03227, phone: +370 5 2744755; e-mail: stanislovas.staras@el.vgtu.lt

Introduction

Helical and meander structures are applied for retardation of electromagnetic waves in the super-wide-band electronic devices. Models of helical systems are proposed and their properties are described in [1, 2] and other monographs and papers. According to analysis, sometimes we can obtain desirable characteristics of the systems using effects that appear due to their inhomogeneities. This possibility is demonstrated in [3] where properties of the system consisting of two unshielded helices are described.

Two types of symmetrical systems are possible: systems with plane symmetry and axially symmetrical systems. According to [3] it is possible to design a simple helical system having good dispersion properties, but it is difficult to ensure low characteristic impedance using the system with plane symmetry.

In the central part of the helical system with the plane symmetry currents flow in opposite directions [1, 2]. In the central part of the axially symmetrical helical system, currents flow in the same direction. As a result of this, the magnetic flux, the distributed inductivity and the characteristic impedance of the axially symmetrical system are lower.

In order to reveal properties and possible advantages of the axially symmetrical helical systems we propose its models and present results of simulation in this paper. The multi-conductor line method [1–3] and the *CST* software package *Microwave Studio* [4] are used for simulation and analysis.

Simulation using the method of multi-conductor lines

In order to reveal general properties of the axially symmetrical helical system (Fig. 1), we will use the multi-conductor line method [2] as in [3].

The model of the system (Fig. 1) is presented in Fig. 2. It consists of the four-row multi-conductor line and shields. The space between conductors is vacuumed.

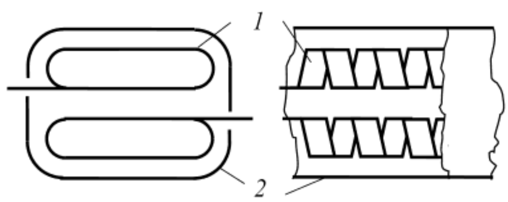


Fig. 1. Axially symmetrical helical line (*1* – helix; *2* – shield)

Using the quasi-TEM approximation and taking into account normal modes, we have the following expressions [1, 2] for voltages and currents of the conductors in the line:

$$\underline{U}_{mn}(x)=\begin{vmatrix}\underline{U}_{1n}\\ \underline{U}_{2n}\\ \underline{U}_{3n}\\ \underline{U}_{4n}\end{vmatrix}=\begin{vmatrix}1 & 1 & 1 & 1\\ 1 & -1 & 1 & -1\\ -1 & 1 & 1 & -1\\ -1 & -1 & 1 & 1\end{vmatrix}\cdot\begin{vmatrix}\underline{U}_1\\ \underline{U}_2\\ \underline{U}_3\\ \underline{U}_4\end{vmatrix}, \quad (1)$$

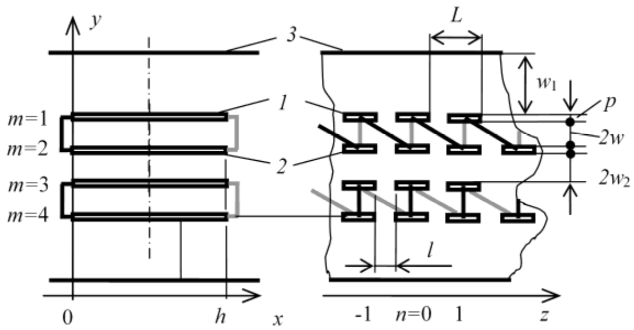


Fig. 2. The model of the axially symmetrical helical line: *1*, *2* – conductors of the multi-conductor line; *3* – shield

$$\underline{I}_{mn}(x)=\mathrm{j}\begin{vmatrix}\underline{I}_{1n}\\ \underline{I}_{2n}\\ \underline{I}_{3n}\\ \underline{I}_{4n}\end{vmatrix}=\begin{vmatrix}Y_{1E0} & Y_{1E\pi} & Y_{1M0} & Y_{1M\pi}\\ Y_{2E0} & -Y_{2E\pi} & Y_{2M0} & -Y_{2M\pi}\\ -Y_{2E0} & Y_{2E\pi} & Y_{2M0} & -Y_{2M\pi}\\ -Y_{1E0} & -Y_{1E\pi} & Y_{1M0} & Y_{1M\pi}\end{vmatrix}\cdot\begin{vmatrix}\underline{I}_1\\ \underline{I}_2\\ \underline{I}_3\\ \underline{I}_4\end{vmatrix}, \quad (2)$$

$$\underline{U}_i=(\underline{A}_{i1}\sin kx+\underline{A}_{i2}\cos kx)\mathrm{e}^{-\mathrm{j}n\theta}, \quad (3)$$

$$\underline{I}_i=(\underline{A}_{i1}\cos kx-\underline{A}_{i2}\sin kx)\mathrm{e}^{-\mathrm{j}n\theta}, \quad (4)$$

where A – coefficients, m – the number of the row of the multi-conductor line, n – the number of the conductor in the row, $k=\omega/\mathrm{c}$ – the wave number, ω – the angular frequency, c – the light velocity, θ – the phase angle between the voltages on the adjacent conductors of the multi-conductor line; $Y_{1E0}=Y_{1E}(0,\theta)$, $Y_{1E\pi}=Y_{1E}(\pi,\theta)$, $Y_{2E0}=Y_{2E}(0,\theta)$ and $Y_{2E\pi}=Y_{2E}(\pi,\theta)$ – characteristic admittances of the multi-conductor line at the electrical wall in the plane *x*0*z*; $Y_{1M0}=Y_{1M}(0,\theta)$, $Y_{1M\pi}=Y_{1M}(\pi,\theta)$, $Y_{2M0}=Y_{2M}(0,\theta)$ and $Y_{2M\pi}=Y_{2M}(\pi,\theta)$ – characteristic admittances of the multi-conductor line at the magnetic wall in the plane *x*0*z*. We can assume that the type of the wall does not have influence on the impedances of the outside rows with m = 1 and m = 4. Then $Y_{1E0}=Y_{1M0}=Y_{10}$ and $Y_{1E0}=Y_{10\pi}=Y_{1\pi}$. The models for calculation of admittances are presented in [5]. The finite difference and the finite element methods were used for calculations.

The section of the multi-conductor line models the axially symmetrical helical system if these symmetry and boundary conditions are satisfied:

$$\underline{U}_{2n}(x)=-\underline{U}_{3n}(x); \quad (5)$$

$$\underline{I}_{2n}(x)=\underline{I}_{3n}(x); \quad (6)$$

$$U_{1n}(0)=U_{2(n+1)}(0); \quad (7)$$

$$I_{1n}(0)=-I_{2(n+1)}(0); \quad (8)$$

$$U_{1n}(h)=U_{2n}(h); \quad (9)$$

$$I_{1n}(h)=-I_{2n}(h). \quad (10)$$

Substituting (1) and (2) into (5)–(10), we arrive at a set of algebraic equations. Solving the set, we can derive the following dispersion equation:

$$\begin{aligned}&2(Y_{10}+Y_{2E0})(Y_{10}+Y_{2M0})\cot^2(\theta/2)=\\ &=(Y_{1\pi}Y_{2M0}+Y_{10}Y_{2M\pi})\cot^2(kh/2)+\\ &+Y_{10}Y_{2E\pi}+Y_{1\pi}Y_{2E0})\tan^2(kh/2)-\\ &-(2Y_{10}Y_{1\pi}+Y_{2E0}Y_{2M\pi}+Y_{2E\pi}Y_{2M0}).\end{aligned} \quad (11)$$

Solving the dispersion equation we can find values of phase angle θ, corresponding to selected values of the wave number k. After that we can find values of the retardation factor K_r and frequency f:

$$K_\mathrm{r}=\mathrm{c}/v_\mathrm{ph}=\theta/kL, \quad (8)$$

$$f=k\mathrm{c}/2\pi, \quad (9)$$

here v_ph – the phase velocity of the traveling-wave and L – the step of the conductors of the helix and multi-conductor line.

The input impedance of the system is dependent on the coordinate x. At $x=0$, according to (1) and (2)

$$Z_\mathrm{C}(0)=\frac{U_{20}(0)}{I_{20}(0)}. \quad (10)$$

Thus

$$Z_\mathrm{C}(0)=\mathrm{j}\frac{1}{Y_{2M\pi}}\frac{\mathrm{j}A+B}{\mathrm{j}C+D}, \quad (11)$$

where

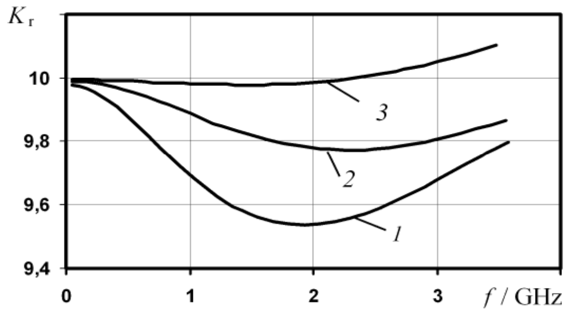
$$A=2(Y_{10}+Y_{2M0})\cot(\theta/2),$$

$$\begin{aligned}B=&(Y_{10}+Y_{1\pi}+Y_{2E0}-Y_{2E\pi})\tan^2(kh/2)+\\ &+(Y_{1\pi}-Y_{10}-Y_{2M\pi}-Y_{2M0}),\end{aligned}$$

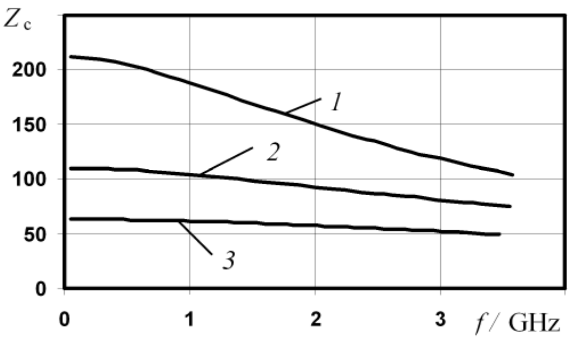
$$C=-2\frac{Y_{2M0}}{Y_{2M\pi}}(Y_{10}+Y_{2E0})\tan(kh/2)\cot(\theta/2),$$

$$\begin{aligned}D=&-\left(\frac{Y_{2M0}}{Y_{2M\pi}}Y_{1\pi}+Y_{10}\right)\cot(kh/2)+\\ &+\left((Y_{10}+Y_{2E0})-\frac{Y_{2M0}}{Y_{2M\pi}}(Y_{1\pi}-Y_{2E\pi})\tan(kh/2)\right).\end{aligned}$$

As an example, a set of characteristics of the axially



(a)



(b)

Fig. 3(a) Retardation factor and (b) characteristic impedance versus frequency at h = 10, L = 2, l = 1, p = 0.25:
1 – $w_1 = w = w_2$ = 1; *2* – $w_1 = w = w_2$ = 0.5;
3 – $w_1 = w = w_2$ = 0.25. Dimensions – mm

symmetrical system (retardation factor and input impedance versus frequency) is presented in Fig. 3.

According to [1, 2] the retardation factor of a single unshielded helix at low frequency is low. It increases with frequency and approaches the constructive retardation factor $K_{\text{rc}} = 2h/L$ (here $2h$ corresponds to the turn length and L is the step of helical turns).

The characteristic impedance of the axially symmetrical helical structure periodically changes along the helical wire. Using properties of electrodynamic structures with periodical inhomogeneities [6–9], it is possible to increase the retardation factor of the axially symmetrical line at low frequency, approach it to the constructive retardation, and reduce the dispersion of the slow electromagnetic wave in the line (Fig. 3(a)). According to (11), retardation factor at low frequency becomes equal to the constructive retardation factor if $Y_{1\pi} = 2Y_{10} = Y_{2E\pi} = 2Y_{2M\pi} = 2Y_{2E0} = 2Y$ and $Y_{2Mo} = 0$.

The input impedance of the axially symmetrical system (Fig. 3(b)) decreases if the distance between helices decreases and it can be sufficiently lower than the input impedance of the helical line with the plane symmetry.

Simulation using the package *Microwave Studio*

The multi-conductor line method allows us relatively easily to find the way to obtain desired properties of the periodic electrodynamic structures. On the other hand, it is used to model infinitively long systems. Besides, changes of characteristic impedances of vertical parts of the helical wires (Fig. 1) are not taken into account when the simplest model (Fig. 2) is used. In order to verify the conclusions based on the multi-conductor method, the *CST* software package *Microwave Studio* was used for simulation of the system presented in Fig. 1.

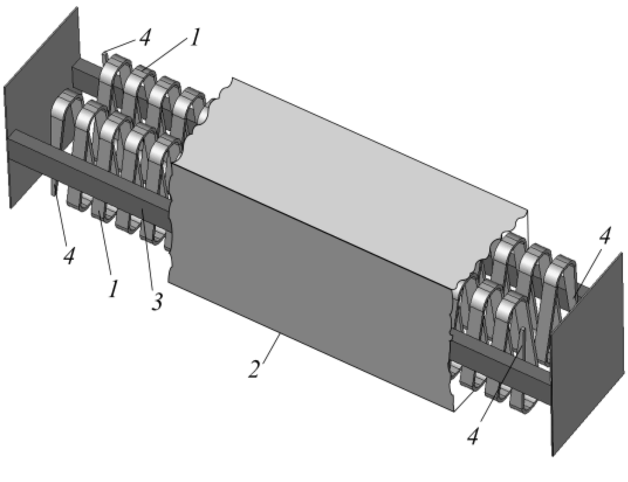


Fig. 4. The model of the symmetrical helical system with axial symmetry: *1* – helix; *2* – shield; *3* – holder; *4* – port

The model of the symmetrical helical systems with axial symmetry, developed using the *CST Microwave Studio* graphical editor, is presented in Fig. 4. The calculation methodology of characteristics of slow-wave structures using the package *Microwave Studio* is described in [8].

The set of curves illustrating dispersion properties of the helical system with axial symmetry (Fig. 4) is presented in Fig. 5. Characteristics confirm that there are possibilities to increase the retardation factor at low frequency and reduce dispersion. According to Fig. 5 the dispersion of retardation is less than (3–4) %.

The values of the system characteristic impedances in the low frequency region are 212, 110 and 63 Ω. according to Fig. 3(b), and 173, 98 and 59 Ω as a result of calculations using *CST Microwave Studio* package. So the values of the characteristic impedance in the low frequency region determined using the *CST Microwave Studio* package are lower (by 6–18 %) with respect to the values when the multi-conductor line method was used.

The differences of retardation factor frequency dependences and characteristic impedances can be explained taking into account that the analyzed system investigated by the *Microwave Studio* package was not infinitively long (Fig. 2) but has the real length and input and output ports (Fig. 4).

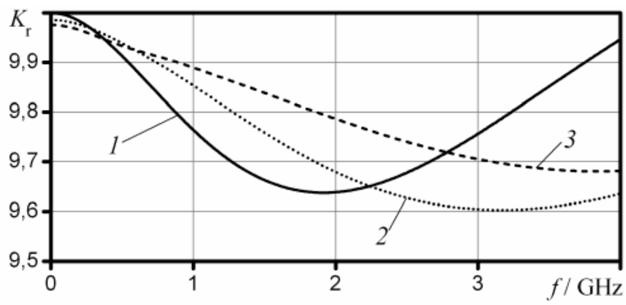


Fig. 5. Retardation factor versus frequency at h = 10, L = 2, l = 1, p = 0.25: *1* – $w_1 = w = w_2 = 1$; *2* – $w_1 = w = w_2 = 0.5$; *3* – $w_1 = w = w_2 = 0.25$. Dimensions – mm

The transfer characteristics of the axially symmetrical helical delay line (length – 40 mm) are presented in Fig. 6. Oscillations of characteristics are caused by reflections from the ports of the system [10]. They increase with frequency because the characteristic impedance of the system decreases with frequency (Fig. 3(b)). The period of the ripples (in the frequency domain) is related to the delay time in the system ($\Delta f \cong 1/2t_{\text{d}}$, where Δf is the period of the ripples and t_{d} is the delay time).

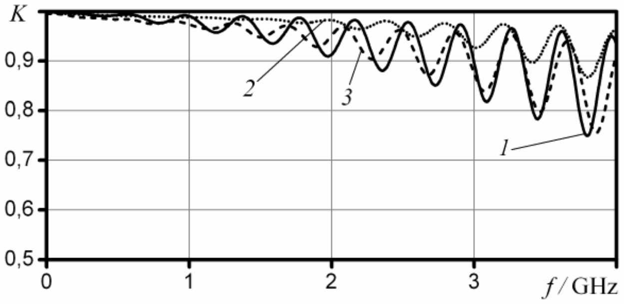


Fig. 6. The amplitude frequency responses of the helical delay line with axial symmetry at h = 10, L = 2, l = 1, p = 0.25:
1 – $w_1 = w = w_2 = 1$; *2* – $w_1 = w = w_2 = 0.5$
3 – $w_1 = 0$ $w = w_2 = 0.25$. Dimensions – mm

According to Fig. 6, the amplitude frequency distortions are less than 3 dB in the frequency range from 0 to 4 GHz. The comparison of these results with those obtained in [3] shows that at properly selected dimensions the axially symmetrical helical systems ensure the wider pass-band with respect to the plane symmetry systems.

Conclusions

Properties of the helical line with axial symmetry are revealed using the multi-conductor line method and the *CST* software package *Microwave Studio*.

There are possibilities to design simple symmetrical helical lines with axial symmetry (Fig. 1) having good dispersion properties and relatively low characteristic impedance.

Simulation made using the *CST Microwave Studio* package confirmed the properties of the systems obtained using the multi-conductor line method.

We recommend to use the synergy of multi-conductor method and a commercial package for analysis and design of the wide-band helical and meander structures. The multi-conductor line method allows relatively easily to find the way to obtain desired properties of a structure. A modern commercial package allows to model the structure with the real length and ports and can be used for the final analysis and design.

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V. Daškevičius, J. Skudutis, S. Štaras. Simulation of the Axially Symmetrical Helical Line // Electronics and Electrical Engineering. – Kaunas: Technologija, 2009. – No. 1(89). – P. 101–104.

Properties of the axially symmetrical helical line are considered in the paper. Models of systems based on the multi-conductor line method and the *CST Microwave Studio* software package are used. The expressions for the retardation factor and the input impedance of the system are derived using the multi-conductor line method. Analysis of the retardation factor allowed to show that there are possibilities to design simple axially symmetrical small-size helical systems having good dispersion properties and relatively small characteristic impedance. Simulation made using the *CST Microwave Studio* package confirmed the properties of the systems revealed using the multi-conductor line method. Synergy of various methods can be effectively used at analysis and design of wide-band periodic structures. Ill. 6, bibl. 10 (in English, summaries in English, Russian and Lithuanian).

В. Дашкевичюс, Ю. Скудутис, С. Штарас. Моделирование осесимметричной спиральной системы // Электроника и электротехника. – Каунас: Технология, 2009. – № 1(89). – С. 101–104.

Рассматриваются свойства осесимметричной спиральной системы, состоящей из двух плоских спиралей. Составлены модели системы. Для анализа применен метод многопроводных линий и пакет программ *CST Microwave Studio*. Выведены выражения коэффициента замедления и входного сопротивления. Анализ выражения коэффициента замедления показал, что есть возможности создать конструктивно простые малогабаритные спиральные системы с хорошими дисперсионными свойствами и необходимым волновым сопротивлением. Моделирование с применением пакета *CST Microwave Studio* подтвердило выводы, сделанные с использованием метода многопроводных линий. Ил. 6, библ. 10 (на английском языке, рефераты на английском, русском и литовском яз.).

V. Daškevičius, J. Skudutis, S. Štaras. Ašinės simetrijos spiralinės sistemos modeliavimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2009. – Nr. 1(89). – P. 101–104.

Nagrinėjamos savybės sistemos, sudarytos iš dviejų ekranuotų spiralių, kurių elementai simetriški ašies atžvilgiu. Sudarytas sistemos modelis. Analizei panaudotas daugialaidžių linijų metodas ir programų paketas *CST Microwave Studio*. Išvestos lėtinimo koeficiento ir įėjimo varžos išraiškos. Remiantis lėtinimo koeficiento išraiška ir skaičiavimų rezultatais parodyta, kad galima sukurti mažų matmenų sistemas, pasižyminčias geromis dispersinėmis savybėmis ir reikiama bangine varža. Skaičiavimai, atlikti taikant programų paketą *CST Microwave Studio*, patvirtino išvadas, padarytas remiantis daugialaidžių linijų metodu. Tiriant ir projektuojant plačiajuostes periodines sistemas verta, išnaudoti daugialaidžių linijų metodo ir pasirinkto komercinio programų paketo sinergiją. Il. 6, bibl. 10 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).

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