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Simulation of Symmetrical and Asymmetrically Shielded Helical Lines

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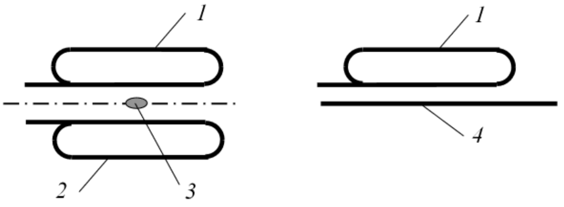
Introduction

Helical structures are applied for retardation of electromagnetic waves in traveling-wave tubes, traveling-wave cathode-ray tubes, delay lines and other electronic devices [1–4]. Models of helical systems are proposed and their properties are described in [2] and other monographs and papers. On the other hand, new opportunities appear for analysis of complicated structures due to the development of new methods and software for simulation of electromagnetic fields and design of microwave devices [5, 6].

Usually symmetrically shielded helical systems are considered and applied in electronic devices. Besides them, practically unshielded helices are sometimes used. For example, a symmetrical system, consisting of two helices, can be used for deflection of the electronic beam in the traveling wave cathode-ray tubes. The cross-section of the system is presented in Fig. 1(a). When the odd electromagnetic wave is excited, properties of such a symmetrical system are identical to properties of the system, consisting of a helix and a shield (Fig. 1(b)).

There is a lack of information about properties of unshielded symmetrical and asymmetrically shielded asymmetrical helical systems. For this reason we present models and results of simulation of the mentioned systems. The multi-conductor line method [1, 2] and the *CST* software package *Microwave Studio* [6] are used for simulation and analysis.



(a) (b)

Fig. 1. Cross-sections of helical systems: *1*, *2* – helix; *3* – lectron beam; *4* – shield

Simulation using the method of multi-conductor lines

In order to reveal the general properties of the systems (Fig. 1) we will use the multi-conductor line method [2].

The model of the asymmetrical system (Fig. 1(b)) is presented in Fig. 2. It consists of the two-row multi-conductor line and shields.

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:

$$\underline{U}_{mn}(x)=\left[\begin{array}{r}(-1)^{n-1}\left(\underline{A}_1\sin kx+\underline{A}_2\cos kx\right)+\\ +\left(\underline{A}_3\sin kx+\underline{A}_4\cos kx\right)\end{array}\right]\mathrm{e}^{-\mathrm{j}n\theta)}, \quad (1)$$

$$\underline{I}_{mn}(x)=$$
$$=\mathrm{j}\left[\begin{array}{l}(-1)^{n-1}Y_m(\pi,\theta)\left(\underline{A}_1\cos kx-\underline{A}_2\sin kx\right)+\\ +Y_m(0,\theta)\left(\underline{A}_3\cos kx-\underline{A}_4\sin kx\right)\end{array}\right]\mathrm{e}^{-\mathrm{j}n\theta}, \quad (2)$$

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, $Y_m(\pi,\theta)$ and $Y_m(0,\theta)$ – characteristic admittances of the multi-conductor line.

The section of the multi-conductor line models the helical system if these boundary conditions are satisfied at $x=0$ and $x=h$:

$$U_{1n}(0)=U_{2n}(0)\,; \quad (3)$$

$$I_{1n}(0)=-I_{2n}(0)\,; \quad (4)$$

$$U_{1n}(h)=U_{2(n+1)}(h)\,; \quad (5)$$

$$I_{1n}(h)=-I_{2(n+1)}(h)\,. \quad (6)$$

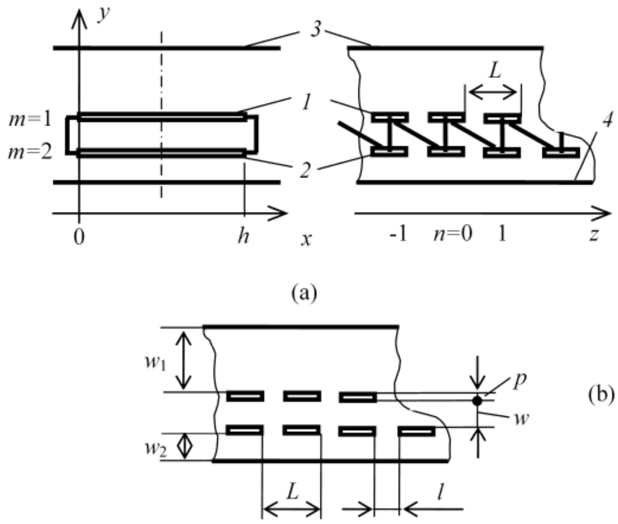


Fig. 2. The model of the asymmetrical helical line (a); the cross-section of the multi-conductor line (b): *1, 2* – conductors of the two-row multi-conductor line, *3, 4* – shields

Substituting (1) and (2) into (3)–(6), we arrive at a set of algebraic equations. Solving the set we can derive the following dispersion equation:

$$\cot^2(kh) = \frac{(Y_{10}+Y_{20})^2\cot^2(\theta/2) - (Y_{10}-Y_{20})(Y_{2\pi}-Y_{1\pi})}{(Y_{1\pi}+Y_{2\pi})(Y_{20}+Y_{10}) + (Y_{10}-Y_{20})(Y_{2\pi}-Y_{1\pi})}, \qquad (7)$$

where $Y_{m0} = Y_m(0,\theta)$, $Y_{m\pi} = Y_m(\pi,\theta)$.

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:

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

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

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

During calculations, values of characteristic impedances $Y_m(\pi,\theta)$ and $Y_m(0,\theta)$ can be found using formula [1, 2]:

$$Y_m(j,\theta) = Y_m(j,0) + \left[Y_m(j,\pi) - Y_m(j,0)\right]\cos^2(\theta/2). \qquad (10)$$

Here $j = \pi; 0$. The finite difference or finite element methods can be used for calculation of characteristic impedances $Y(\pi,0)$, $Y(\pi,\pi)$, $Y(0,0)$ and $Y(0,\pi)$ [7, 8].

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

$$Z_{\mathrm{C}2}(0) = \frac{U_{20}(0)}{I_{20}(0)}. \qquad (11)$$

Thus

$$Z_{\mathrm{C}2}(0) = \frac{Y_{20}+Y_{10}}{Y_{2\pi}(Y_{20}+Y_{10}) - Y_{20}(Y_{2\pi}-Y_{1\pi})} \cdot \left(\cot(\theta/2) + j\frac{Y_{2\pi}-Y_{1\pi}}{Y_{20}+Y_{10}}\right)\tan(kh). \qquad (12)$$

At low frequency, when $kh \to 0$ and $\theta \to 0$, we can simplify the dispersion equation and obtain this expression for the retardation factor:

$$K_\mathrm{rLF} = \frac{2h}{L}(Y_{10}+Y_{20}) \Big/ \sqrt{(Y_{1\pi}+Y_{2\pi})(Y_{20}+Y_{10}) + (Y_{10}+Y_{20})(Y_{2\pi}+Y_{1\pi})}. \qquad (13)$$

At high frequency, when the electromagnetic field becomes concentrated at the helix conductor and characteristic impedances approach each other ($Y_{10} \cong Y_{1\pi} \cong Y_{20} \cong Y_{2\pi}$), the retardation factor is determined by the length $2h$ and the step L of helix wires:

$$K_\mathrm{rHF} \cong 2h/L. \qquad (14)$$

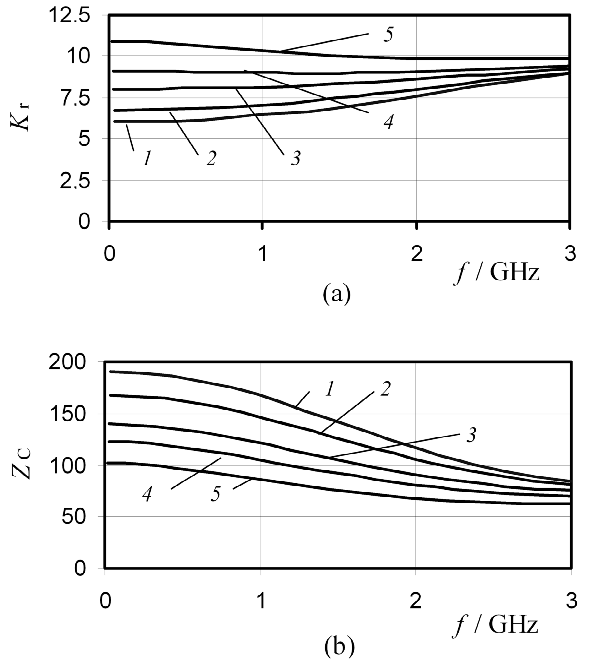
According to (12) in the case, when the distance between the helix and shields is constant along the helix wires and $Y_{10} = Y_{20} = Y_0$, $Y_{1\pi} = Y_{2\pi} = Y_\pi$, the retardation factor is given by

$$K_\mathrm{rLF} = \frac{2h}{L}\sqrt{\frac{Y_0}{Y_\pi}}. \qquad (15)$$

Thus, at a constant distance between the helix and the shields, the retardation factor at low frequency is less than at high frequency. Analyzing (13), we see that the retardation factor at low frequency increases if the distance between the helix and the upper shield (Fig. 2) increases (Y_{10} and $Y_{1\pi}$ increase with respect to Y_{20} and $Y_{2\pi}$). So, at asymmetrical disposition of shields or using the asymmetrically shielded asymmetrical helix system (Fig. 1(b)) and also the symmetrical system (Fig. 1(a)) we can reduce dispersion of the retardation factor with respect to dispersion in the asymmetrical helical system, containing the shield at a constant distance from the helix.

Calculations of characteristics confirmed the latter idea. As an example, a set of characteristics of the asymmetrical system (retardation factor and input impedance versus frequency) is presented in Fig. 3. According to Fig. 3(a), approaching the shield to one side of a helix (Fig. 1(b)) or reducing the distance between helices in the symmetrical system (Fig. (a)), we can control and reduce the dispersion of retardation and phase velocity of the electromagnetic wave. At a shorter distance between a helix and a shield or the distance between the helices, the characteristic impedance becomes lower and less dependent on frequency.

Therefore, there is a possibility to control the dispersion properties of the symmetrical and asymmetrical helical systems (Fig. 1) and reduce the phase-frequency



(a)

(b)

Fig. 3. Retardation factor (a) and characteristic impedance versus frequency (b) at h = 10, L = 2, l = 1; w_1 =10, w = 1.5 mm: *1* – w_2 = 2; *2* – w_2 = 1.5; *3* – w_2 = 1; *4* – w_2 = 0.75; *5* – w_2 = 0.5 mm

distortions of propagating signals at relatively high characteristic impedance of the retard system.

Simulation using the package *Microwave Studio*

The multi-conductor line method allows us model infinitively long retard 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 systems presented in Fig. 1.

The models of the symmetrical and asymmetrical helical systems, developed using the *CST Microwave Studio* graphical editor, are presented in Fig. 4 and Fig. 5. The calculation methodology of characteristics of slow-wave structures using the package Microwave Studio is described in [8].

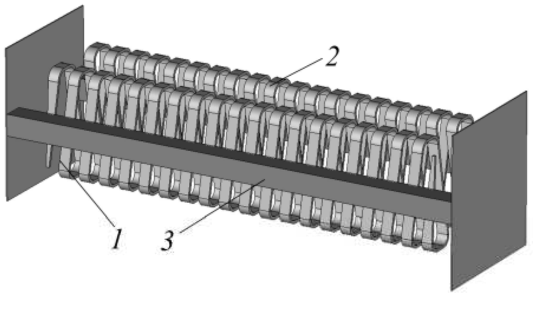


Fig. 4. The model of the symmetrical helical system: 1, 2 – helix; 3 – holder

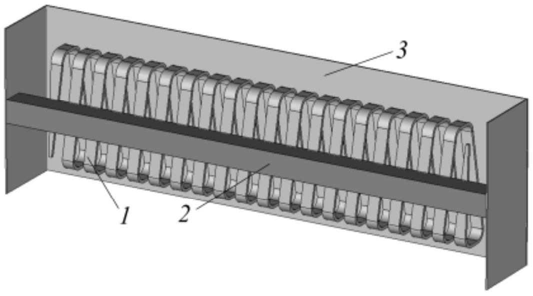


Fig. 5. The model of the asymmetrical helical system: 1 – helix; 2 – holder, 3 – shield

The set of curves illustrating dispersion properties of the asymmetrical helical system (Fig. 5) is presented in Fig. 6. Characteristics are similar to those of curves in Fig. 3(a).

The approximate values of characteristic impedance in the low frequency region determined using the package *CST Microwave Studio* were lower (by 10-25 %) with respect to the values when the multi-conductor method was used. The differences between the results decrease if the distance between the helix and shields becomes longer.

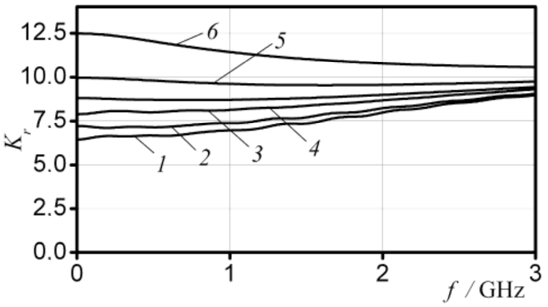


Fig. 6. Retardation factor versus frequency at h = 10, L = 2, l = 1; w_1 =10, w = 1.5 mm: *1* – w_2 = 2; *2* – w_2 = 1.5; *3* – w_2 = 1; *4* – w_2 = 0.75; *5* – w_2 = 0.5; *6* – w_2 = 0.25 mm

Analysis of calculation results revealed the cause of the differences. They are related to the scatter of the electric field and increase of the capacitances at the ends of the system at removing of a shield from one side of the system [9].

The amplitude frequency response of the asymmetrical

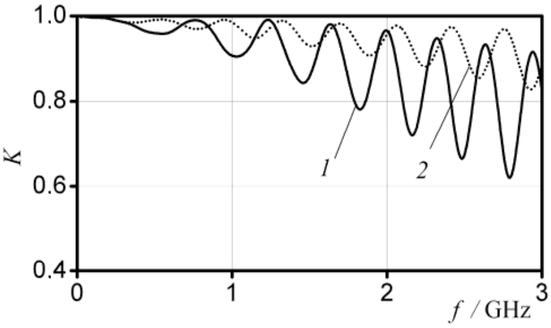


Fig. 7. The amplitude frequency responses of the asymmetrical helical line at h = 10, L = 2, l = 1; w_1 =10, w = 1.5: *1* – w_2 = 2; *2* – w_2 = 0.5 mm

system at minimal dispersion of retardation is presented in Fig. 7 (curve 2). According to it, the amplitude frequency distortions are less than 3 dB in the band from 0 to 3 GHz.

Conclusions

1. Properties of the symmetrical helical system and asymmetrical system containing the asymmetrical shield are revealed using the multi-conductor line method and the *CST* software package *Microwave Studio.*
2. The multi-conductor line method allowed us to show that there are possibilities to design the simple helical symmetrical systems or asymmetrical systems (Fig. 1) having good dispersion properties and relatively high characteristic impedance.
3. Simulation made using the package *CST Microwave Studio* confirmed the properties of the systems discovered using the multi-conductor line method.

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Properties of the unshielded symmetrical and asymmetrically shielded asymmetrical helical systems are considered in the paper. Models of systems based on the multi-conductor method and the *CST Microwave Studio* software package are used. The expressions for the retardation factor and the input impedance of the systems are derived using the multi-conductor line method. Analysis of the retardation factor allowed us to show that there are possibilities to design the simple helical symmetrical systems or asymmetrical systems having good dispersion properties and relatively high characteristic impedance. Simulation made using the package *CST Microwave Studio* confirmed the properties of the systems discovered using the multi-conductor line method. Ill. 7, bibl. 9 (in English; summaries in English, Russian and Lithuanian).

В. Дашкевичюс, Ю. Скудутис, С. Штарас. Моделирование симметричной и асимметрически экранированной спиральной системы // Электроника и электротехника. – Каунас: Технология, 2008. – № 3(83). – С. 3–6.

Рассматриваются свойства неэкранированной симметричной спиральной системы и асимметричной системы, состоящей из плоской спирали и экрана с одной стороны спирали. Составлены модели систем. 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 спиральные системы с хорошими дисперсионными свойствами и сравнительно большим волновым сопротивлением. Моделирование с применением пакета *CST Microwave Studio* подтвердило выводы, сделанные с использованием метода многопроводных линий. Ил. 7, библ. 9 (на английском языке; рефераты на английском, русском и литовском яз.).

V. Daškevičius, J. Skudutis, S. Štaras. Simetrinės ir asimetriškai ekranuotos spiralinės sistemos modeliavimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2008. – Nr. 3(83). – P. 3–6.

Nagrinėjamos neekranuotos simetrinės spiralinės sistemos ir asimetrinės sistemos, sudarytos iš ištęsto skerspjūvio spiralės ir šalia jos esančio ekrano, savybės. Sudaryti sistemų modeliai. 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 įmanoma sukurti sistemas, pasižyminčias geromis dispersinėmis savybėmis ir sąlygiškai didele bangine varža. Skaičiavimai, atlikti taikant programų paketą *CST Microwave Studio* patvirtino išvadas, padarytas remiantis daugialaidžių linijų metodu. Il. 7, bibl. 9 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).

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