Properties of Helical Structures with Internal Anisotropic Shields

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***Abstract*—Properties of the helical structures with internal anisotropic shields are considered in the paper. Models of systems based on the multiconductor 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 multiconductor line method. Analysis of the retardation factor allowed to show that there are possibilities to design helical structures with internal anisotropic shields having good dispersion properties and relatively high characteristic impedance. Simulation made using the *CST Microwave Studio* package confirmed the properties of the systems revealed using the multiconductor line method. Furthermore, in addition it allowed the detection of parasitic resonances that are available in helical systems with anisotropic internal shields. Synergy of various methods can be effectively used at analysis and design of wide-band periodic structures.**

***Index Terms*—Delay lines, delay systems, distributed parameter systems, microwave devices, microwave technology.**

I. 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 [5]–[14] and other monographs and papers. Properties of helical systems with internal shields are investigated in [8]. This work shows that retardation factor dependency on frequency can be reduced and the pass-band of system can be extended by using internal shields. If the thickness of the internal shield is increased, the retardation factor in the low frequency band increases. At a certain thickness of the internal shield the systems retardation factor becomes constant over a wide frequency range. However, in this case, the characteristic impedance of system decreases. Other known method for increasing the retardation factor at lower frequencies uses an internal anisotropic shield [9].

In this paper, the investigation results of helical delay systems with internal anisotropic shields are presented. Multiconductor line method and numerical method based *MicroWave Studio* software package are used in this investigation. The pass-band extension options are revealed.

II. THE MODEL OF THE HELICAL STRUCTURE WITH INTERNAL ANISOTROPIC SHIELDS

In order to investigate influence of the internal anisotropic shield on the helical system characteristics, let us firstly consider and examine characteristics of a simplified version of the system (Fig. 1).

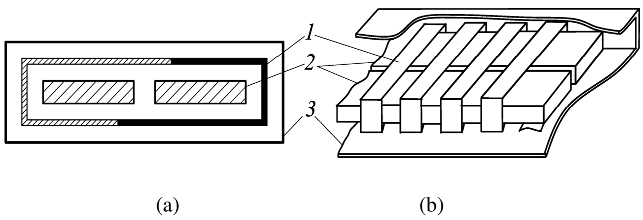

Fig. 1. The cross-section of a helical system (a), and the view of the helix (b): *1* – helix; *2,3* – shields.

This figure shows the system internal and external shields located symmetrically in relation to the helix. Let us assume that the helix conductors are in vacuum. The model of system based on multiconductor line method [10] is shown in Fig. 2.

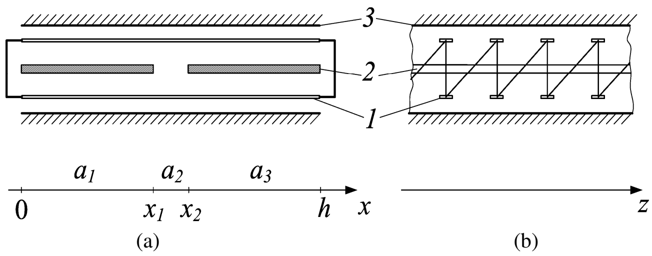

Fig. 2. The model of the helical line (a); cross-section (b): *1* – conductor of the multiconductor line, *2*, *3* – shields, x_i – multiconductor line section end coordinate, h – half the length of the helix coil, a_i – dimensions of the internal parts of the system.

The following dispersion equation and characteristic impedance expressions can be obtained for the investigated simplified model [8]:

$$\tan^2\frac{\theta}{2}=\frac{\cos ka_2\sin k\left(a_1+a_3\right)+\sin ka_2\left(\frac{M}{M_\pi}\cos ka_1\cos ka_3-\right.}{\cos ka_2\cos k\left(a_1+a_3\right)-\sin ka_2\left(\frac{M}{M_\pi}\cos ka_1\sin ka_3+\right.}$$

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$$\frac{\left(-\frac{M_\pi}{M}\sin ka_1 \sin ka_3\right)\cos ka_2 \sin k\left(a_1+a_3\right)+\sin ka_2 \times}{\left(+\frac{M_\pi}{M}\sin ka_1 \cos ka_3\right)\cos ka_2 \cos k\left(a_1+a_3\right)-\sin ka_2 \times}$$

$$\frac{\times\left(\frac{M_0}{M}\cos ka_1 \cos ka_3-\frac{M}{M_0}\sin ka_1 \sin ka_3\right)}{\times\left(\frac{M_0}{M}\cos ka_1 \sin ka_3+\frac{M}{M_0}\sin ka_1 \cos ka_3\right)}, \quad (1)$$

$$Z_{IN}=\frac{1}{\tan(\theta/2)}\frac{\cos ka_2 \sin k\left(a_1+a_3\right)+\sin ka_2 \times}{\cos ka_2 \cos k\left(a_1+a_3\right)-\sin ka_2 \times}$$

$$\frac{\times\left(\frac{M_0}{M}\cos ka_1 \cos ka_3-\frac{M}{M_0}\sin ka_1 \sin ka_3\right)}{\times\left(\frac{M_0}{M}\cos ka_1 \sin ka_3+\frac{M}{M_0}\sin ka_1 \cos ka_3\right)}, \quad (2)$$

where $M=M(\theta)$ is the characteristic admittance of the one-row multiconductor line in the model, $M_0=M\left(0,\theta\right)$ and $M_\pi=M\left(\pi,\theta\right)$ are dual-row multiconductor line characteristic admittance in the gap area of the shield, $k=\omega/c_0$ is the wavenumber, ω is the angular frequency, c_0 is the speed of light in the free space. The internal shield gap, whose width is a_2, is placed symmetrically, so $a_1=a_3$.

Retardation factor and characteristic impedance expressions at low frequencies can be obtained from (1) and (2)

$$k_{\mathrm{R\,LF}}=k_{\mathrm{R\,s}}\sqrt{\left(1-\frac{a_2}{h}\left(\frac{M}{M_\pi}-1\right)\right)\left(1+\frac{a_2}{h}\left(\frac{M_0}{M}-1\right)\right)}, \quad (3)$$

where $k_{\mathrm{R\,s}}$ is the structural retardation factor.

$$Z_{\mathrm{IN\,LF}}=\frac{k_{\mathrm{R\,s}}}{k_{\mathrm{R\,LF}}}\left(\frac{a_1+a_3}{h}\cdot\frac{1}{M}+\frac{a_2}{h}\cdot\frac{1}{M_\pi}\right). \quad (4)$$

At high frequencies, as in other systems, where conductors are in vacuum, $k_{\mathrm{R\,HF}}=k_{\mathrm{R\,s}}$, $Z_{\mathrm{IN\,HF}}=1/M$.

It follows from presented expressions that the gap in the internal shield affects the system retardation factor at low and medium frequencies. When the gap is narrow ($a_2 << h$), expression (3) can be simplified and written as follows

$$k_{\mathrm{R\,LF}}=k_{\mathrm{R\,s}}\left(1+\frac{a_2}{2h}D\right), \quad (5)$$

where

$$D=\frac{M}{M_\pi}+\frac{M_0}{M}-2. \quad (6)$$

The last expression shows that the retardation factor $k_{\mathrm{R\,LF}}$ is dependent on characteristic admittance ratios. An assessment is needed that at low frequencies $M_0 < M_\pi \le M$. When the internal shield is thin, $M_\pi \approx M$, $D<0$, and the gap reduces $k_{\mathrm{R\,LF}}$. The internal shield thickening increases the factor D (5) and $k_{\mathrm{R\,LF}}$. When $D>0$, the retardation factor at lower frequencies becomes higher than the structural retardation factor $k_{\mathrm{R\,s}}$, and increase of $k_{\mathrm{R\,LF}}$ is greater if the width of the gap in the internal shield is greater.

According to (3) – (5) and investigation of other helical structures [10], the different influence of the gap onto systems dispersion properties can be explained as follows. On one hand, electromagnetic fields interaction between the flat helix parts arises because of the gap and this decreases $k_{\mathrm{R\,LF}}$. On the other hand, when $M > M_\pi$, the gap changes the characteristic admittance along the helix conductor, and because of this increases $k_{\mathrm{R\,LF}}$.

Characteristics of the helix system with internal anisotropic shield calculated using (1) and (2) are shown in Fig. 3.

The above characteristics indicate that thickening the internal shield of the helical system with a longitudinal gap really can increase the system retardation factor in the low frequency range (Fig. 3(b), curves *3* and *4*), and at the same time allows to reduce the phase delay dispersion in a wide frequency range and to widen the pass-band of the system. In order to reduce the system's input impedance dependency on frequency, its value should be reduced in the low-frequency range and increased in the high frequency range. This can be achieved by bringing the shields closer to the helix (Fig. 3(b), curve *4*).

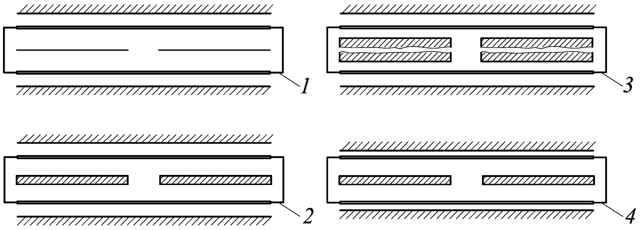
III. SIMULATION USING THE PACKAGE MICROWAVE STUDIO

The multiconductor line method allows us to simulate infinitively long slow-wave 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 multiconductor method, the *CST* software package *Microwave Studio* was used for simulation of the system presented in Fig. 4.

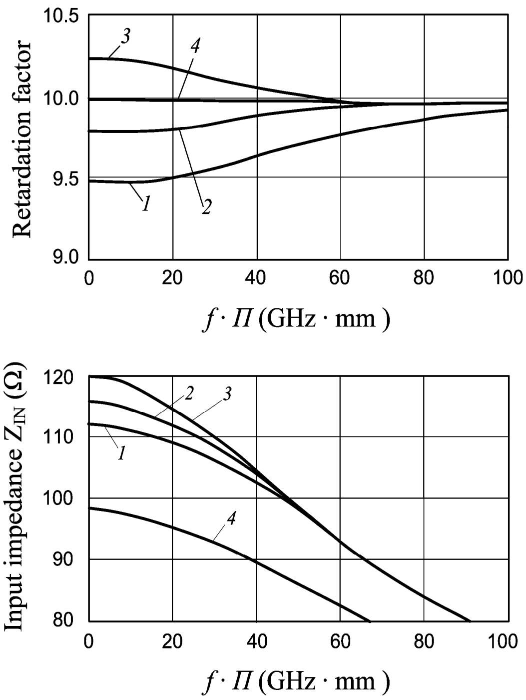
The model of helical system with an internal anisotropic shield model was created by using the package graphical editor. The methodology of simulation is described in [10]. The calculated system retardation factor versus frequency is presented in Fig. 5.

Analysis of the calculation results shows that thickening the internal shield really allows to increase the retardation factor in the low frequency range (Fig. 5, curves *1* and *3*). Gap in the internal shield also increases the system retardation factor in the low frequency range (Fig. 5, curves *4* and *5*). The thick shield with a gap gives the biggest effect (Fig. 5, curve *4*).

Thus, the results obtained using the software package *Microwave Studio* confirmed the results obtained using multiconductor line method. At the same time, it is important to notice that using *Microwave Studio* package internal resonances were detected in the systems with anisotropic shield, when the shield gap width is greater than the distance between the helix and the internal shield $a_2 > \left(w - p_1/2\right)$ (Fig. 6).



(a)

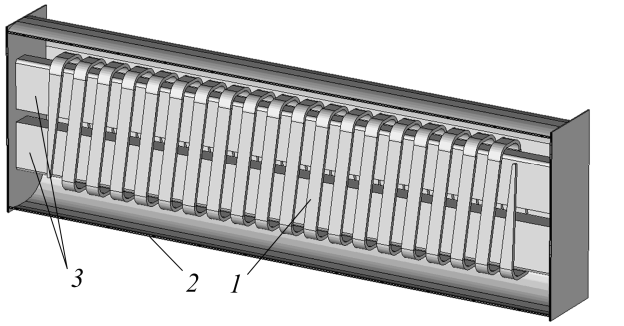


(b)

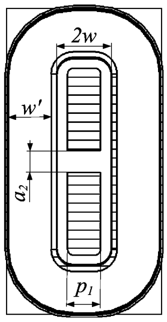
Fig. 3. The cross-sections of the helical system with internal anisotropic shields (a), and retardation factor and input impedance of the helical system (b) versus frequency at $k_{Rs} = 10$, $l = 0.5L$, $p = 0.125L$, $\varepsilon_r = 1$, $x_1 = 0.4h$, $x_2 = 0.6h$, $x_{31} = x_{41} = \ldots = x_7 = 10$, $w_{im} = 0.5L$, l – width of the helical conductor, p – thickness, L – step, i – number of the segment of the multiconductor line, m – number of the conductor of the line, w_{im} – the distance between the helix and the internal shield, w'_{im} – the distance between the helix and the external shield, w_2 – thickness of the internal shield, the external and internal regions of the helix filled by dielectric with relative dielectric permittivity , Π – helix turn perimeter: ε_r=1: *1* – w_2=0.5L, w'_{im}=0.5L; *2* – w_2=L, w'_{im}= 0.5L; 3 – w_2 = 5L, w'_{im}=0.5L; *4* – w_2 = 2L, w'_{im}=0.35L.

We can consider the anisotropic internal shield as a two-wire line short-circuited at its ends. Then the first resonance is possible at wavelength 2l, where l is the length of the two-wire line (like in other helical systems [10]). According to this, at l = 44 mm, the first resonant frequency must be approximately 3.4 GHz. According to Fig. 5 (curve *4*), the first resonance occurs at twice less frequency.

We can explain the last effect taking into account that the current that is returning along the internal anisotropic shield cannot repeat the current path that is flowing in the helix conductor, and the return path in the internal shield has almost twice the length.



(a)



(b)

Fig. 4. The model of the helical system with internal anisotropic shield: *1* – helix; *2* – external shield, *3* – internal shield: (a) – general view, (b) – the cross section; 2w – helix thickness, p_1 – internal shield thickness, w' – distance between the helix and the external shield, a_2 – the internal shield gap width.

Examination of the distribution of the current density in the internal shield confirms this idea (Fig. 6).

The amplitude frequency responses of the helical system containing anisotropic internal shield are presented in Fig. 7. According to Fig. 6 and 7, two parasitic resonances appear in the frequency range up to 5 GHz at the length of the system of 44 mm and other dimensions corresponding to characteristic *4* in Fig. 5.

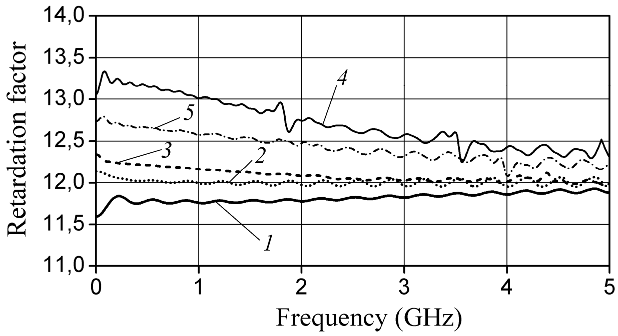


Fig. 5. Retardation factor versus frequency at h = 10, L = 2, l = 1; h =10, w' = 2; 2w = 2.5; p = 0.25: *1* – p_1 = 1.5; a_2 = 0; *2* – p_1 = 2; a_2 = 0; *3* – p_1 = 1.5; a_2 = 1; *4* – p_1 = 2; a_2 = 1; *5* – p_1 = 2; a_2 = 0,5 mm.

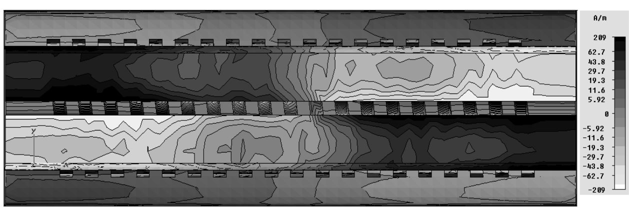


Fig. 6. Surface current longitudinal component distribution in the system cross-section at 1.841 GHz (corresponding to Fig. 5, curve *4*). Cutting plane is vertically at the middle of the internal shield gap.

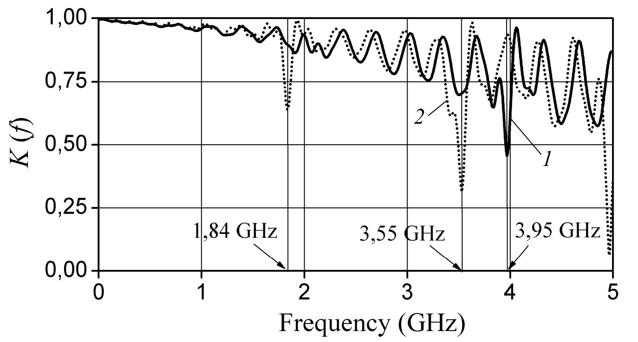


Fig. 7. The amplitude-frequency responses of the helical system: *1* – curve corresponds to the system, which retardation factor is shown in Fig. 5 by curve *5*, and characteristic *2* – by curve *4*.

The wavelength of the second resonance is approximately twice greater than the length of the system.

At small gap in the anisotropic shield, resonant effects have less influence onto characteristics of the helical system (Fig. 5, curve *4*, and Fig. 7, curve *1*).

Thus, when using broadband helical delay systems with anisotropic internal shields attention should be given to the possible parasitic resonances that may affect the system performance. The following investigations of the electromagnetic field distribution in the system cross-section and frequency characteristics have shown that resonance can be avoided by reducing the thickness of the internal anisotropic shield (by increasing the gap between the helix and the internal shield). However, this is followed by decrease the retardation factor in low frequency range. Parasitic resonance effect can be also reduced by reducing the internal anisotropic shield gap area 5-th curve in Fig. 5. When $a_2 < \left(w - p_1/2\right)$ the system resonances were noted.

It is also important that, according to (6), it is possible to avoid resonances due to parts of the internal shield using a thin conductor shortening them (using H-type internal shield).

IV. Conclusions

Properties of the helical line with internal anisotropic shields are revealed using the multiconductor line method and the *CST* software package *Microwave Studio.*

The multiconductor line method allowed us to show that there are possibilities to design the helical asymmetrical systems (Fig. 4) or symmetrical systems with internal anisotropic shields 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 multiconductor line method. At the same time, using the *Microwave Studio* we were able to detect a possibility of parasitic resonances occurring in such systems. Possible methods to avoid the mentioned resonances are showed.

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