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Electrodynamical Analyses of Dielectric and Metamaterial Hollow-core Cylindrical Waveguides

L. Nickelson, T. Gric, S. Asmontas
Semiconductor Physics Institute, Teraherzt's Electronics Laboratory,
A.Gostauto str. 11, LT-01108 Vilnius, Lithuania, phone: +37067103291; e-mail: nick@pfi.lt

R. Martavicius
Electronics Faculty, Vilnius Gediminas Technical University,
Naugarduko str. 41, LT-03227 Vilnius, Lithuania, phone: +37068556833; e-mail: romanas.martavicius@el.vtu.lt

Introduction

Silicium fibers with small losses appeared in 1970. This event has laid the foundation for modern optical communication industry. However Si waveguides have some nonlinearity which occurs when electromagnetic waves interact with core of the waveguide [1]. This core is made of some material. To do away with this problem it was begun to use hollow-core waveguides (HCW) with walls of good reflectivity. In general, hollow waveguides are an attractive alternative to solid-core fibers because of the inherent advantage of their air core. The HCW is a hole in the solid medium. This hole is a canal where microwaves can propagate.

Hollow waveguides have the following main advantages: low insertion loss, ruggedness and small beam divergence [2]. HCWs are also characterized by large broadbandwidth at a certain waveguide radius. These properties make them highly successful. HCWs have been widely used in modern telecommunication infrastructure.

An electrodynamical analyze of different waveguides [3−5] is important in creation of microwave devices.

In the last decade there has been huge interest in composite materials with untraditional electrodynamic characteristics, for example, negative permittivity or (and) permeability and usage of these materials in waveguide technique. The composite materials are created from metallic structures in the form of spirals and strips that are doted in basic material. These artificially made materials are named metamaterials. The functional electromagnetic properties of metamaterials arise due to the ability to perfectly combine the resonant electric or (and) magnetic characteristics designing the sub-wavelength resonator elements (spirals, strips) [6].

In this article we consider dielectric and metamaterial hollow-core cylindrical waveguides (HCWs). Electrodynamical characteristics of the HCW depend on the radius of the hole r, the surrounded medium permittivity ε_r^d *or* ε_r^m and permeability μ_r^d *or* μ_r^m (later we will designate as $\varepsilon_r^{d,m}$ and $\mu_r^{d,m}$), where upper indexes *d*, m mean dielectric or metamaterial medium correspondingly.

The dispersion equation of the HCW

A solution of Maxwell's equations to analyze HCW (Fig. 1) is presented in this part. The method we have used to solve our waveguide problem is based on two approaches. The first is the coupled mode method and the second is the partial area method.

The presentation of longitudinal components of the electric field E_z^a and the magnetic field H_z^a that satisfies to Maxwell's equations in an air medium is as follows:

$$E_z^a = A_1 \mathrm{J_m}\left(k_\perp^a r\right)\exp(i\mathrm{m}\varphi)\,, \tag{1}$$

$$H_z^a = B_1 \mathrm{J_m}\left(k_\perp^a r\right)\exp(i\mathrm{m}\varphi), \tag{2}$$

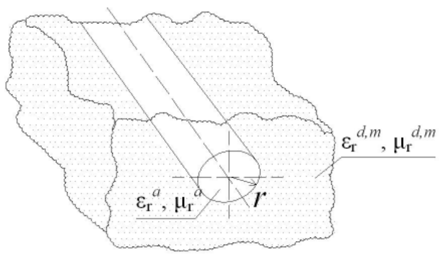

Fig. 1. HCW model

where A_1, B_1 are unknown arbitrary amplitudes, $\mathrm{J_m}$ is the Bessel function of the m−th order, $k_\perp^a$ is the transverse propagation constant of the air medium, r is the radius of the HCW, m is the azimuthal index characterizing azimuthal variations of the field, φ is the azimuthal angle.

The presentation of longitudinal components of the electric $E_z^{d,m}$ and magnetic $H_z^{d,m}$ fields that satisfies to Maxwell's equations in the dielectric or metamaterial infinite medium is as follows:

$$E_z^{d,m} = A_2 \mathrm{H_m}\left(k_\perp^{d,m}\, r\right)\exp(im\varphi), \tag{3}$$

$$H_z^{d,m} = B_2 \mathrm{H_m}\left(k_\perp^{d,m}\, r\right)\exp(im\varphi), \tag{4}$$

where $\mathrm{H_m}$ – the Hankel function of the m–th order and the second kind.

We have expressed azimuthal components E_φ, H_φ through longitudinal components E_Z, H_Z and equated tangential components to each other. The satisfied boundary conditions are as follows: $E_z^a = E_z^{d,m}$, $H_z^a = H_z^{d,m}$, $E_\varphi^a = E_\varphi^{d,m}$, $H_\varphi^a = H_\varphi^{d,m}$. We have obtained the system of algebraic equations which is homogeneous. The condition of solvability of this system is the requirement of equality of its determinant Δ to zero. The determinant of the system yields the dispersion equation for the waveguide under our consideration. This determinant has fourth order and can be presented as follows:

$$\Delta = \eta^2 \cdot \chi^2 \cdot h^2 \cdot \mathrm{m}^2 \cdot \left(\frac{1}{\left(k_\perp^{d,m}\right)^2 \cdot r} - \frac{1}{\left(k_\perp^{a}\right)^2 \cdot r} \right)^2 +$$
$$+ \left[\eta \cdot \eta' \cdot \chi \cdot \chi'\right] \cdot \frac{k^2}{k_\perp^a \cdot k_\perp^{d,m}} \cdot \left[\varepsilon_\mathrm{r}^{d,m} \cdot \mu_\mathrm{r}^{a} + \varepsilon_\mathrm{r}^{a} \cdot \mu_\mathrm{r}^{d,m}\right] -$$
$$-\eta^2 \cdot \left(\chi'\right)^2 \cdot \frac{\varepsilon_\mathrm{r}^{d,m} \cdot \mu_\mathrm{r}^{d,m} \cdot k^2}{\left(k_\perp^{d,m}\right)^2} - \left(\eta'\right)^2 \cdot \chi^2 \cdot \frac{\varepsilon_\mathrm{r}^{a} \cdot \mu_\mathrm{r}^{a} \cdot k^2}{\left(k_\perp^{a}\right)^2} = 0, \tag{5}$$

where $\eta = \mathrm{J_m}\left(k_\perp^a \cdot r\right)$, $\chi = \mathrm{H_m}\left(k_\perp^{d,m} \cdot r\right)$, η' and χ' are derivatives of magnitudes η and χ correspondingly, $\varepsilon_\mathrm{r}^{d,m}$ and $\varepsilon_\mathrm{r}^{a}$ are the permittivity of the dielectric, metamaterial and the air medium correspondingly, $\mu_\mathrm{r}^{d,m}$ and μ_r^{a} are the permeability of the dielectric, metamaterial and the air medium correspondingly. Magnitudes $k_\perp^{d,m}$ and $k_\perp^{a}$ are related with the longitudinal propagation constant and the permittivity and permeability of the dielectric, metamaterial or the air medium as follows: $k_\perp^{d,m} = \left(k^2 \cdot \varepsilon_\mathrm{r}^{d,m} \cdot \mu_\mathrm{r}^{d,m} - h^2\right)^{1/2}$, $k_\perp^{a} = \left(k^2 \cdot \varepsilon_r^{a} \cdot \mu_r^{a} - h^2\right)^{1/2}$, where $k = \omega/c$ – the wave number in the air medium, *h* is the longitudinal propagation constant.

We have obtained the dispersion equations in the form of a determinant and created a computer program in MATLAB to investigate dielectric and metamaterial HCWs.

Approbation of the computer algorithm for analysis of HCW dispersion characteristics

Our computer algorithm is based upon the dispersion equation Eq. (5). We have found longitudinal propagation constants *h* as roots of this dispersion equation. Testing of our computer algorithm was made using data from the article [7]. In this article dispersion characteristics of the open cylindrical dielectric rod waveguide are given. We have substituted these values of some magnitudes: $\varepsilon_\mathrm{r}^a = 4$, $\varepsilon_\mathrm{r}^{d,m} = 1, \mu_\mathrm{r}^{a} = \mu_\mathrm{r}^{d,m} = 1$, r = 10 mm in our computer algorithm (in spite the fact, that there is the air medium inside the HCW, $\varepsilon_\mathrm{r}^a = 4$ to test the program). In Fig. 2 and 3 dispersion curves from the article [7] are designated by the black dots. Dispersion characteristics of the dielectric rod waveguide drawn by our computer program are shown by the solid line.

In Fig. 2 we present dispersion characteristics from the article [7] and dispersion curves drawn using our computer algorithm for modes with the azimuthal index of m = 1.

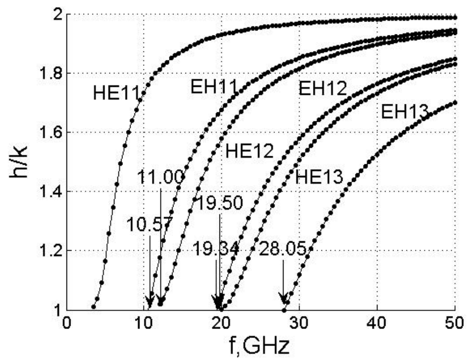

Fig. 2. The dielectric rod dispersion characteristics of hybrid modes, when m = 1, $\varepsilon_\mathrm{r}^a = 4$, r = 10 mm

We see that the comparison of our calculations with data from the article [7] has pointed out the high accuracy of coincidence. In Fig. 2 we can see $\mathrm{HE_{11}}$, $\mathrm{HE_{12}}$, $\mathrm{HE_{13}}$, $\mathrm{EH_{11}}$, $\mathrm{EH_{12}}$, $\mathrm{EH_{13}}$ hybrid modes.

We have also tested our computer algorithm for modes with the azimuthal index of m = 0. In Fig. 3 dispersion characteristics from the article [7] and our calculations for axis-symmetric modes with the azimuthal index of m = 0 are shown.

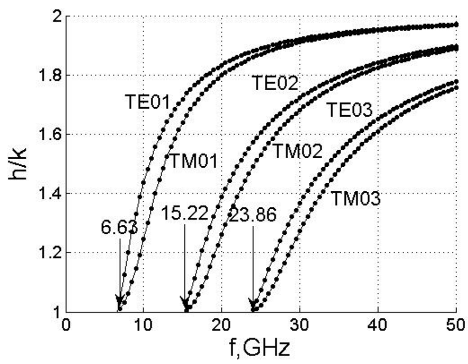

Fig. 3. The dielectric rod dispersion characteristics of axis-symmetric modes, when m = 0, $\varepsilon_\mathrm{r}^a = 4$, r = 10 mm

In Fig. 3 we can see axis-symmetric TM_{01}, TM_{02}, TM_{03}, TE_{01}, TE_{02}, TE_{03} modes with azimuthal index of m = 0. Fig. 3 shows that our calculations and data from the article [7] agree with one another.

The numerical results

Electrodynamical characteristics of the dielectric and metamaterial HCW have been analyzed changing the permittivity $\varepsilon_r^{d,m}$ and the permeability $\mu_r^{d,m}$ of the material which surrounds the air canal. We have also calculated dispersion characteristics of the dielectric and metamaterial HCWs changing values of the radius (r = 1mm, 3mm, 10mm).

The permittivity and the permiability of the air media inside the waveguide hole are $\varepsilon_r^a = 1$ and $\mu_r^a = 1$ corespondingly. The azimuth index used making numerical calculations is m = 1. Dispersion characteristics of the dielectric and metamaterial HCWs drawn by our computer program are shown by the solid line and black dots.

Dispersion characteristics of dielectric HCWs

Analyzing of the dielectric HCW has been realized in the wide frequency range from 10 till 120 GHz. We have got dispersion characteristics of the dielectric HCW, when the permittivity is $\varepsilon_r^d = 11.8$ (high-resistance semiconductor n-Si) and the permeability is $\mu_r^d = 1$.

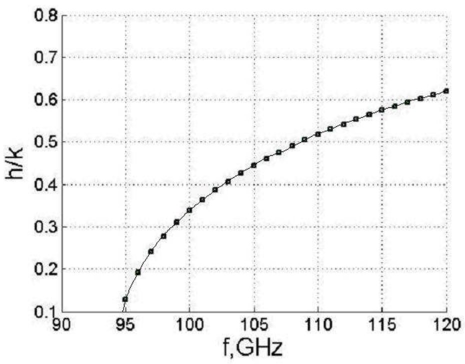

Fig. 4. The dielectric HCW' dispersion characteristic of the main mode, when r = 1 mm, $\varepsilon_r^d = 11.8$, $\mu_r^d = 1$

In Fig. 4 we see, that the dielectric HCW with the radius which is equal to 1 mm has got only one mode at the wide frequency range (10−120 GHz). The main mode cutoff frequency is about 94 GHz.

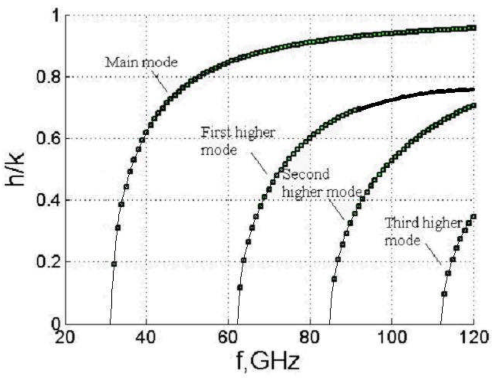

Fig. 5. The dielectric HCW' dispersion characteristics, when r=3 mm , ε_r^d= 11.8, $\mu_r^d = 1$

In Fig. 5 we see, that the dielectric HCW with the radius which is equal to 3 mm has got four modes in the considered frequency range. The main mode cutoff frequency is about 31 GHz, the first highest mode cutoff frequency is about 62 GHz. The second and third highest modes cutoff frequencies are about 84 and 116 GHz, correspondingly.

Comparing dispersion characteristics shown in Fig. 4 and 5 we see, that the cutoff frequency of the main mode strongly shifts from 95 GHz (r = 1mm) till 31 GHz (r = 3mm).

Fig. 6 points out that the dielectric HCW with radius r = 10 mm is a many-mode waveguide. We see fifteen modes at the frequency range 10−120 GHz. In this case the main mode cutoff frequency is about 9 GHz. The second and third highest modes cutoff frequencies are about 19 and 25 GHz, correspondingly.

Comparing dispersion characteristics shown in Fig. 4−6 we see that the cutoff frequency of the main mode strongly shifts from 95 GHz (r = 1mm) till 9 GHz (r = 10mm). Comparing dispersion characteristics of the second highest mode from Fig. 5 and 6 we see that the cutoff frequency strongly shifts from 62 GHz (r = 3 mm) till 19 GHz (r = 10 mm). The same tendency of displacement of the cutoff frequency we can observe for all the highest modes. We can make a conclusion that the larger radius of the dielectric HCW is the smaller values of the main and the highest modes cutoff frequencies are.

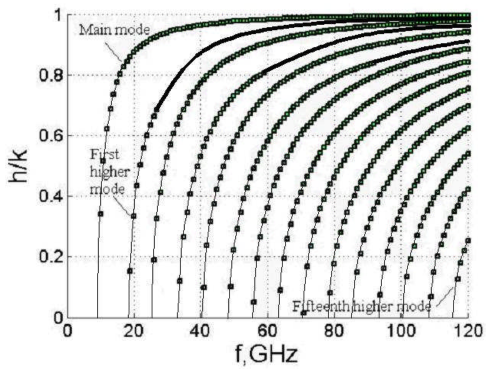

Fig. 6. The dielectric HCW' dispersion characteristics, when r=10 mm ε_r^d= 11.8, $\mu_r^d = 1$

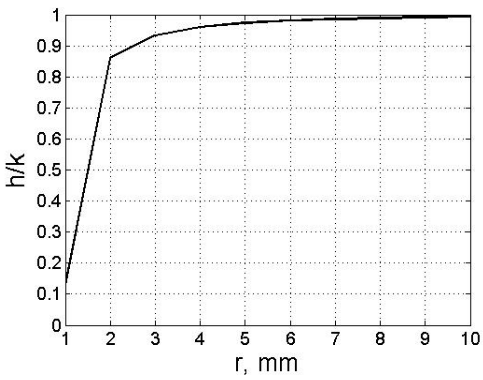

Fig. 7. Dependence of the normalized propagation constant h/k on the radius of the dielectric HCWs at the frequency of f = 95 GHz

Fig. 7 presents a dependence of ratio of h and k values (normalized longitudinal propagation constant h/k) on a dielectric HCW radius. We can see that this dependence is very strong till radius is equal to 2 mm. This dependence is appreciable till a radius is equal to 5 mm. The curve of this dependence is saturated after r = 7.5 mm.

Dispersion characteristics of metamaterial HCWs

In this section we present an electrodynamical analyses of metamaterial HCWs. Metamaterial in this case is initialized with medium which a unit cell consists of three layers. There are three strips in the first and the third layers, and two rings in the second layer [8]. Certain values of the metamaterial permittivity ε_r^m and permeability μ_r^m are given in table 1.

Table 1 Values of the metamaterial permittivity and permeability at the 75-115 GHz frequency range (region of "humps" is shown in grey color) [8]

***f*, GHz**	$\boldsymbol{\varepsilon_r^m}$	$\boldsymbol{\mu_r^m}$
75	-41.25	1.17
77.5	-37.5	1.17
80	-35.83	1.17
82.5	-33.75	1.17
85	-32.5	1.25
87.5	-31.25	1.33
90	-30	1.5
92.5	-35	2
95	-27.5	1.83
97.5	-7.5	1.25
100	-5	-0.5
102.5	-10	-0.5
105	-8.75	0.17
107.5	-8.75	0.33
110	-10	0.5
112.5	-10	0.5
115	-10.83	0.5

Dispersion characteristics of metamaterial HCWs have been analyzed in the frequency range of 75−115 GHz because only in this range we know the values of magnitudes ε_r^m and μ_r^m.

Firstly we have analyzed the case when radius of the metamaterial HCW is 1 mm.

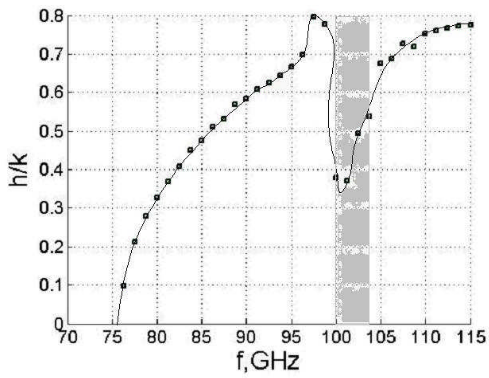

Fig. 8. The metamaterial HCW' dispersion characteristics of the main mode when r = 1 mm

In Fig. 8 we see, that when r = 1mm, there is only the one mode in the metamaterial HCW. The cutoff frequency of this main mode is f_c = 75.83 GHz. A very interesting strong effect when magnitudes of the permittivity ε_r^m and permeability μ_r^m of metamaterial simultaneously become negative is observed. We see a "hump" of the dispersion characteristic in Fig. 8.

In Fig. 9 we see, that when r = 3 mm, there are 4 modes in the metamaterial HCW.

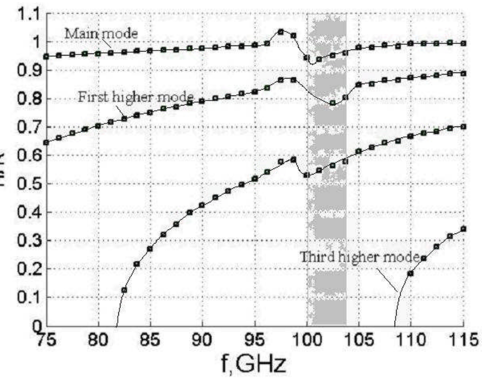

Fig. 9. The metamaterial HCW' dispersion characteristics, when r = 3 mm

We cannot determine the cutoff frequencies of the main mode and the first highest mode. The main reason of it is that values of the permittivity and permeability of the metamaterial are known after f = 75 GHz. We have also analyzed dispersion characteristics of the metamaterial HCW with r = 10 mm.

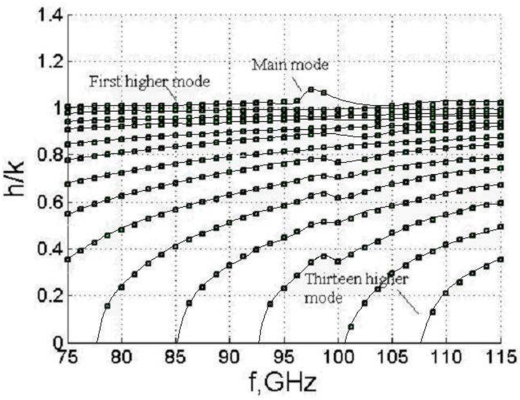

Fig. 10. The metamaterial HCW' dispersion characteristics, when r = 10 mm

In the Fig. shown in the article [8], we can see the tendency of diminution of the permittivity curve at the frequency range (100 -104 GHz) and the tendency of the growth of the permeability curve at the same frequency range. This is the reason of the presence of "humps" in Fig. 8-10. The regions of "humps" are shown in these Figs. in grey color. The "jumps" of the dispersion curves shown in Fig. 8-10 can also be explained by the presence of the double-negative permittivity and permeability at the frequency range (100-104 GHz). At this frequency range the argument of the Hankel function is always real. At frequencies, when phenomenon of double-negativity is absent, the argument of the Hankel function is always the imaginary quantity.

Comparing Fig. 8−10 we can come to the conclusion, that the larger radius of the metamaterial HCW is, the larger number of modes propagated in such waveguide is. When radius of the metamaterial HCW was 1 mm, there was the one main mode in the waveguide (see Fig. 8), when radius of the waveguide was 3 mm, there were 4 modes in the waveguide (see Fig. 9). When radius of the metamaterial HCW was 10 mm, there were 14 modes in the waveguide (see Fig. 10).

We have graphically viewed dependence of the normalized propagation constant h/k on radius of the metamaterial HCW at the frequency of f = 95 GHz. The got result for the main mode is presented in Fig. 11.

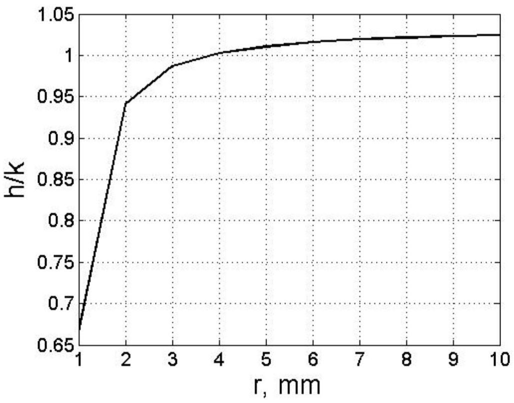

Fig. 11. Dependence of the normalized propagation constant h/k on the radius of the metamaterial HCWs at the frequency of f = 95 GHz

In Fig. 11 we see, that the larger radius of the metamaterial HCW is, the larger value of the normalized propagation constant h/k for the main mode is.

Analyzing dispersion characteristics of the dielectric HCWs we can draw an interesting conclusion: ratio of h and k values for these waveguides can be $h/k \leq 1$ (see Fig. 4-7). Such waveguides is possible to use as delay lines. The same ratio for the metamaterial HCWs can be $h/k \succ 1$ (see Fig. 8-11). Therefore modes propagated in the metamaterial HCW, when $h/k \succ 1$ are the fast.

After we have compared dielectric and metamaterial HCWs with each other we can mention that these waveguides work in one mode regime, when their radius is 1 mm. However when value of the radius increases till r = 10 mm, dielectric and metamaterial HCWs work in the many-mode regimes.

Comparing Fig. 4 and 8 with each other we can notice that the cutoff frequency of the main mode propagated in the dielectric HCW (f_c = 95 GHz) shifts relatively to the value of the cutoff frequency of the main mode propagated in the metamaterial HCW (f_c = 75.42 GHz). Values of the dispersion characteristics for all higher modes also differ strongly.

Comparing values of the dispersion characteristics for the main and the highest modes, shown in Fig. 5 and 9, we see that the difference of these values is not so strong. The same comparison for the dispersion characteristics (Fig. 6 and 10) shows that difference of the normalized propagation constant values is appreciable. It can be explained in the following way. When radius of the waveguide is r = 1 mm, the electromagnetic wave energy propagates in the air canal and in the surrounded medium. For that reason permittivity and permeability of the surrounded medium strongly influences the HCW dispersion characteristics. In the case of the large waveguide radius almost all electromagnetic wave energy propagates inside the air canal. The surrounded medium influence in this case becomes appreciable.

Comparing Fig. 7 with Fig. 11 we can make a conclusion that in both cases dependences are very strong till r = 2mm. However a dependence of the normalized propagation constant h/k on a waveguide radius r in the dielectric HCW earlier becomes saturated. Such case takes place when radius of the dielectric HCW is 6 mm. The dependence of the magnitude h/k on the waveguide radius in the metamaterial HCW slowly grows till r=10 mm. We also see that a magnitude h/k (Fig. 11) becomes larger than one when r becomes larger than 4 mm. We should notice that the normalized propagation constant h/k of the main mode of the metamaterial HCW has larger values than the same one of the main mode of the dielectric HCW. For example, when r = 1 mm value of the normalized propagation constant in the dielectric HCW is 0.15, the value of the same parameter in the metamaterial HCW is 0.68. We see that it is 4.53 times larger.

Conclusions

1. We have got solution of Maxwell's equations to analyze dielectric and metamaterial HCWs and obtained a dispersion equation for these waveguides.
2. We have created the computer algorithm in MATLAB to analyze HCW dispersion characteristics. This computer algorithm has been tested using data from the article [7].
3. We have investigated HCW's dispersion characteristics changing values of the permittivity, permeability and radius. Numerical results have showed that the larger radius of the dielectric and metamaterial HCWs is the larger number of modes propagated in the waveguide is.
4. We have found out the value of the dielectric and metamaterial HCW's radius when only the main mode can propagate in the waveguide.
5. The ratio of h and k values for the dielectric HCW and the metamaterial HCW (till r = 4 mm) is $h/k \leq 1$.Therefore the dielectric HCW and the metamaterial HCW (till r = 4 mm) work as delay lines. When radius of the metamaterial HCW is larger than 4 mm, modes propagated in it are the fast.
6. The larger difference between dielectric and metamaterial HCW's dispersion characteristics is the smaller value of the waveguide radius is.
7. We discover a strong abnormal effect in dispersion characteristics of the Metamaterial Hollow-core Cylindrical Waveguides with simultaneously negative the permittivity ε_r^m and permeability μ_r^m of this material. We assume that this effect can be successfully used for creation of microwave devices, for example, switches.

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Development of computer algorithms for electrodynamical analyses of different waveguides is important nowadays due to the fact that these can be created from the newest materials with complicated dependences of the permittivity and the permeability on frequencies and waveguides can have nanometers sizes. We present the dispersion equation for analyzes of dielectric and metamaterial hollow-core cylindrical waveguides (HCWs). The main objective of our work is to analyze dispersion characteristics of the dielectric and metamaterial HCWs. We have analyzed dispersion characteristics of single−mode and many−mode dielectric and metamaterial HCWs. Dependencies of normalized propagation constant values on waveguide radiuses have been analyzed for dielectric and metamaterial HCWs. We have compared properties of the dielectric HCWs with metamaterial HCWs using obtained graphical results. Ill. 11, bibl. 10 (in English; summaries in English, Russian and Lithuanian).

Л. Никельсон, Т. Гриц, С. Ашмонтас, Р. Мартавичюс. Электродинамический анализ пустотелых диэлектрических и метаматериальных волноводов // Электроника и электротехника. – Каунас: Технология, 2008. – № 2(82). – С. 3–8.

Развитие компьютерных алгоритмов для электродинамического анализа различных волноводов является актуальной задачей нашего времени, т. к. волноводы могут быть изготовлены из новейших материалов со сложными зависимостями диэлектрической и магнитной проницаемости от частоты. Кроме того, отдельные элементы волновода могут быть нанометровых размеров, поэтому только путем расчетов можно подобрать требуемые электродинамические характеристики волновода. В статье представляется дисперсионное уравнение для анализа диэлектрических и метаматериальных пустотелых цилиндрических волноводов (ПЦВ). Основная цель нашей работы заключается в анализе дисперсионных характеристик диэлектрического и метаматериального ПЦВ. В статье представлен анализ дисперсионных характеристик одномодового и многомодовых диэлектрического и метаматериального ПЦВ. Зависимости нормированной продольной постоянной распространения от радиуса волновода были получены для диэлектрического и метаматериального ПЦВ. Используя полученные графические результаты, было проведено сравнение свойств диэлектрического и метаматериального ПЦВ. Ил. 11, библ. 10 (на английском языке; рефераты на английском, русском и литовском яз.).

L. Nickelson, T. Gric, S. Ašmontas, R. Martavičius. Dielektrinių ir metamedžiaginių tuščiavidurių cilindrinių bangolaidžių elektrodinaminė analizė // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2008. – Nr. 2(82). – P. 3–8.

Kompiuterinių algoritmų, skirtų įvairių bangolaidžių elektrodinaminei analizei atlikti, plėtra dabar yra labai aktuali, nes bangolaidžiai gali būti pagaminti iš naujausių medžiagų, turinčių sudėtingas dielektrinės ir magnetinės skvarbos priklausomybes nuo dažnio, ir gali turėti nanometrinius dydžius. Pristatoma dispersinė lygtis, skirta dielektrinių ir metamedžiaginių tuščiavidurių cilindrinių bangolaidžių (TCB) elektrodinaminei analizei atlikti. Plačiai aprašoma dielektrinių ir metamedžiaginių TCB dispersinių charakteristikų analizė. Pateikta vienmodžio bei daugiamodžio dielektrinių ir metamedžiaginio TCB dispersinių charakteristikų analizė. Normuotos išilginės sklidimo pastoviosios priklausomybės nuo bangolaidžio spindulio buvo gautos dielektriniam bei metamedžiaginiam TCB. Naudojant gautus grafinius rezultatus, buvo atliktas dielektrinių bei metamedžiaginio TCB savybių palyginimas. Il. 11, bibl. 10 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).