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The Magnetoactive *p*-Ge Rod Waveguide Loss Analysis on the Concentration of Two Component Hole Charge Carriers

L. Nickelson, A. Bubnelis, A. Baskys
Center for Physical Sciences and Technology,
Gostauto 11, LT- 01108 Vilnius, Lithuania, e-mails: lucynickelson@gmail.com, arturas.bubnelis@gmail.com
Faculty of Electronics, Vilnius Gediminas Technical University,
Naugarduko str. 41, LT-03227, Vilnius, Lithuania, e-mail: algirdas.baskys@vgtu.lt
R. Navickas
Faculty of Electronics, Vilnius Gediminas Technical University,
Naugarduko str. 41, LT-03227, Vilnius, Lithuania, e-mail: romualdas.navickas@vgtu.lt

Introduction

A semiconductor material placed in an external constant magnetic field can be called magnetoactive semiconductor plasma or gyrotropic material. The propagation of electromagnetic (EM) waves in the unbounded magnetoactive semiconductor plasma is analyzed in many works i.e. [1, 2]. The EM wave propagation in the metal waveguide filled with magnetoactive plasma is also studied sufficiently fully [3, 4]. The limited number of works is devoted to analyses of the open (without a metal screen) magnetoactive plasma waveguides. Our present article is dedicated to a study of such waveguides.

On the base of magnetoactive semiconductor plasma waveguides are worked out controllable microwave devices, i.e. phase shifters, modulators, converters, switches, filters [5–7]. The microwave device phase and attenuation can be controlled by an external constant magnetic field as well as optically. Magnetoactive semiconductor waveguides are used also in the development of various optoelectronic, plasmonic devices and lasers [8, 9].

The phase constant dependencies on the frequency of open circular magnetoactive semiconductor waveguides are given in [7, 10, 11]. In the last works the magnetoactive semiconductor waveguide losses are not presented.

As the magnetoactive semiconductor plasma usually possesses high losses, for this reason the study of loss' dependencies on the carrier concentration and frequency are the topic of special interest.

In this article we present the dispersion characteristics of dissipative magnetoactive germanium (Ge) circular cylindrical waveguide when the material contains the different percentages of light and heavy holes. The solution of this boundary problem in the rigorous electrodynamical formulation of the problem was fulfilled by the partial area method with using of the Müller's method for the searching of complex propagation constants [7, 12].

Here for the first time is presented dependencies of the complex longitudinal propagation constant $\underline{h} = h' - \mathrm{i}h''$, where h' is the phase constant and h'' is the waveguide attenuation constant (losses) on the percentage of light hole N_l and heavy hole N_h concentrations and the operating frequency *f*. The investigation was accomplished for the EM wave with the left-handed circular polarization (looking from EM source) when the azimuthal dependence is expressed by $e^{+i\varphi}$ in the wide frequency range from 5 GHz till 200 GHz. These kinds of EM waves are also called the helicon or the extraordinary waves. We have used our created computer software in the MATLAB language. Here is shown a number of important properties of two component hole *p*-Ge waveguides that can be useful to design controllable microwave devices.

Permittivity tensor of magnetoactive *p*-Ge with two component hole carriers

Electrodynamical properties of *p*-Ge semiconductor placed in a constant longitudinal magnetic field are characterized by the relative permittivity tensor $\ddot{\underline{\varepsilon}}_r^{p\text{-Ge}}$ [1, 7]

$$\ddot{\underline{\varepsilon}}_r^{p\text{-Ge}} = \begin{vmatrix} \underline{\varepsilon}_{xx}^{p\text{-Ge}} & \mathrm{i}\underline{\varepsilon}_{xy}^{p\text{-Ge}} & 0 \\ -\mathrm{i}\underline{\varepsilon}_{xy}^{p\text{-Ge}} & \underline{\varepsilon}_{xx}^{p\text{-Ge}} & 0 \\ 0 & 0 & \underline{\varepsilon}_{zz}^{p\text{-Ge}} \end{vmatrix}, \qquad (1)$$

where $\underline{\varepsilon}_{xx}^{p\text{-Ge}}$, $\underline{\varepsilon}_{xy}^{p\text{-Ge}}$, $\underline{\varepsilon}_{zz}^{p\text{-Ge}}$ are the complex permittivity tensor' components:

$$\underline{\varepsilon}_{xx}^{p\text{-Ge}} = \varepsilon_k^{p\text{-Ge}}\left(1-\sum_{n=1}^{2}\left(\frac{\mathrm{i}\omega_{pn}^2}{\omega}\cdot\frac{(\nu_n+\mathrm{i}\omega)}{(\nu_n+\mathrm{i}\omega)^2+\omega_{cn}^2}\right)\right), \qquad (2)$$

$$\underline{\varepsilon}_{xy}^{p\text{-Ge}} = -\varepsilon_k^{p\text{-Ge}}\sum_{n=1}^{2}\left(\frac{\omega_{pn}^2}{\omega}\cdot\frac{\omega_{cn}}{(\nu_n+\mathrm{i}\omega)^2+\omega_{cn}^2}\right), \qquad (3)$$

$$\underline{\varepsilon}_{zz}^{p\text{-Ge}} = \varepsilon_k^{p\text{-Ge}}\left(1-\sum_{n=1}^{2}\left(\frac{\mathrm{i}\omega_{pn}^2}{\omega}\cdot\frac{1}{(\nu_n+\mathrm{i}\omega)}\right)\right), \qquad (4)$$

where $\omega_{pn}^2 = e^2 N_n \big/ m_n^* \varepsilon_0 \varepsilon_k^{p\text{-Ge}}$ is the plasma angular frequency, $\omega_{cn} = eB_0 \big/ m_n^*$ is the cyclotron resonance angular frequency, $\nu_n = e \big/ \mu_n m_n^*$ is the free carriers average collision frequency, ω is the angular operating frequency [7]. The index *n* indicates that the frequencies are calculated for the heavy holes ($n = 1$) or for the light holes ($n = 2$). The tensor components (2) – (4) depend on the germanium parameters such as the material lattice permittivity $\varepsilon_k^{p\text{-Ge}}$, the operating frequency f, the magnetic induction B_0 of external constant magnetic field strength and other [1, 2, 7].

In the present article we give the results of our calculations for the *p*-Ge waveguide when the semiconductor material has two component charge carriers, i.e. heavy and light holes. The tensor components depend on the percentages of certain kind of holes in the comparison with the total concentration *N*. The total concentration *N* is the sum of the light hole N_l and heavy hole N_h concentrations. The altering of rate N_h/N allow us to change the electrical semiconductor parameters. This makes it possible to select the required waveguide electrodynamical characteristics as the broadbandwidth, the losses, the wavelength and the kind of operating mode.

Dependences of the complex propagation constant on the percentage of heavy holes' concentration

Dispersion characteristics of *p*-Ge waveguide are calculated when the ratio of heavy holes' concentration N_h is equal to 10%, 30% and 90% of the total free carrier concentration $N = 5\cdot 10^{19}\,\mathrm{m}^{-3}$. Calculations were fulfilled for the waveguide with the radius equal to $10^{-3}\,\mathrm{m}$, $B_0 = 1$ T, $\varepsilon_k^{p\text{-Ge}} = 16$. The effective mass of *p*-Ge heavy holes is $m_h^* = 0.279 m_e$, the effective mobility is $\mu_h^* = 6.3\ \mathrm{m}^2/\mathrm{V}\cdot\mathrm{s}$. The values for the light holes are: $m_l^* = 0.043 m_e$, $\mu_l^* = 40.9\ \mathrm{m}^2/\mathrm{V}\cdot\mathrm{s}$.

In Fig. 1 – Fig. 6 is given the complex propagation constant dependencies of the main helicon and eight higher helicon modes on frequencies. It is known that the main mode HE_{11} of cylindrical semiconductor waveguide without the external magnetic field B_0 is a hybrid mode with the first and second subscripts equal to 1. As it known the first subscript denotes the number of the EM field variations in the azimuthal direction and the second subscript shows the variations along the waveguide radius. Here are only analyzed modes with the first subscript equal to 1, i.e. the same azimuthal symmetry by φ as the main mode [7]. We do not classify here the investigated hybrid modes of the dissipative gyrotropic waveguide because the mode kind can transform with the changing of frequency.

In Figs 1, 3, 5 we present the normalized real part h'/k_0 of complex propagation constant $\underline{h}$, where k_0 is the wavenumber in a vacuum.

The cutoff frequency f_{cut} of the main mode is 9.4 GHz, 9.1 GHz and 8.2 GHz when the heavy holes' concentration is 10%, 30%, 90% of *N*, respectively (Figs 1, 3, 5). The cutoff frequency of the main mode with increasing of rate N_h/N slowly moves to the lower frequencies. The broadbandwidth of the *p*-Ge waveguide is equal 93% (Fig. 1), 107% (Fig.3), 109% (Fig.5), respectively.

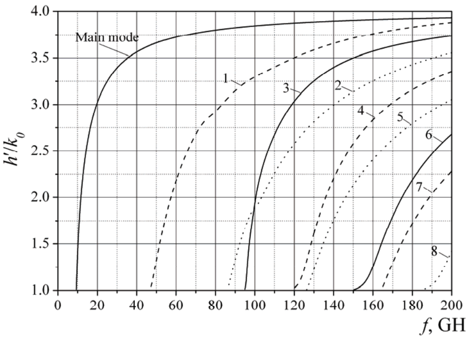
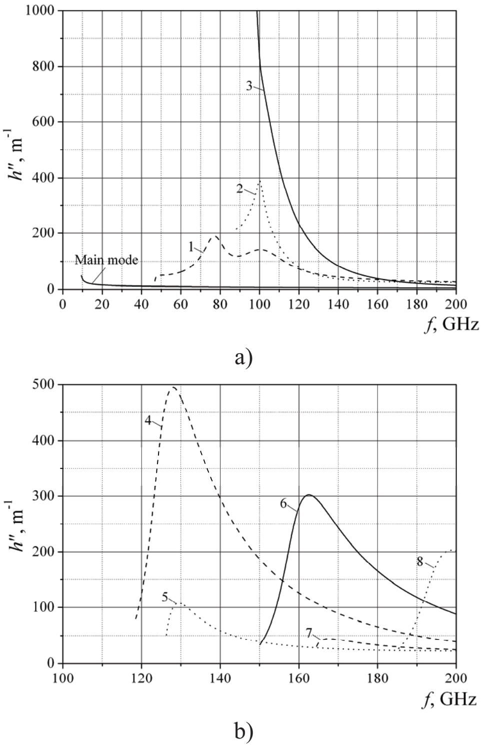


Fig. 1. Dependences of waveguide normalized phase constant on the frequency when the heavy holes' concentration is 10% of the total carrier concentration



a)

b)

Fig. 2. Dependences of waveguide losses on the frequency when the heavy holes' concentration is 10% of total carrier concentration

We have examined the dispersion characteristics at the heavy holes' concentration from 0 till 100% with the step equal to 5%. On this risen we can note the general properties of the dispersion characteristics dependent on concentration N_h. We have observed the transformation of waves with a change of values N_h and *f*. As an example in Fig. 1 we can see the intersection of the second and third higher modes' curves at $f = 100$ GHz. This means that the degeneration of second and third modes is observed at $f = 100$ GHz. The transformation of these modes occurs at frequencies higher than 100 GHz because the second subscript values of these higher modes change by the places.

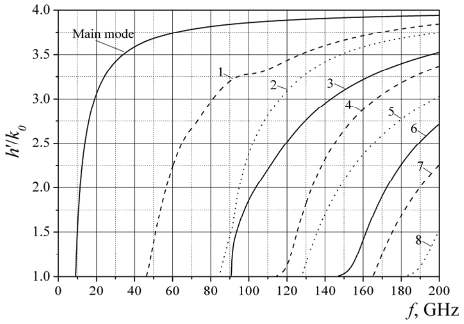
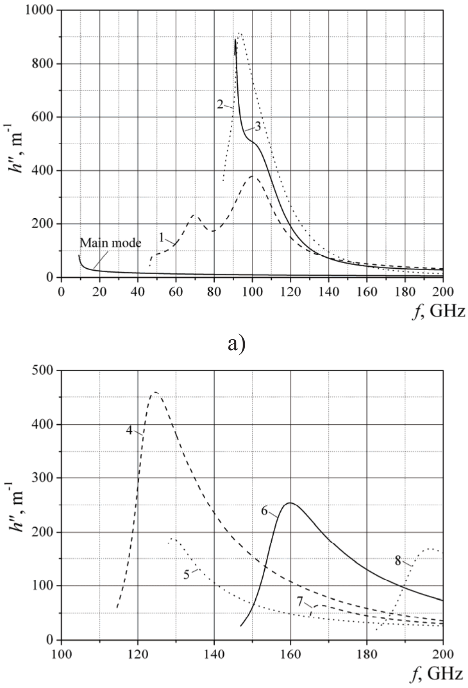


Fig. 3. Dependences of waveguide normalized phase constant on the frequency when the heavy holes' concentration is 30% of the total carrier concentration



a)

b)

Fig. 4. Dependences of waveguide loss on the frequency when heavy holes' concentration is 30% of total carrier concentration

The second and third higher modes' curves detach and degeneration is removed when the heavy holes' concentration is grown till 30% and higher. The second higher mode' cutoff frequency changes noticeably (Fig. 3) in the comparison with the same mode f_{cut} of the previous case (Fig. 1). We see that the first and second higher mode curves intersect at $f = 102.2$ GHz when the heavy holes' concentration is 90% (Fig. 5). The transformation of these higher modes is happened at the frequencies higher than 102.2 GHz.

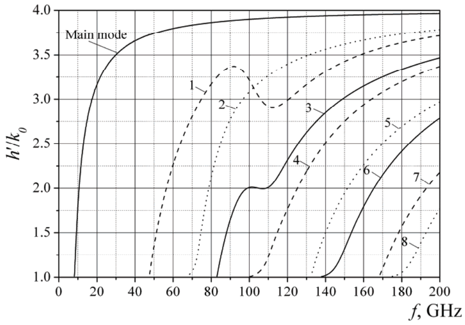
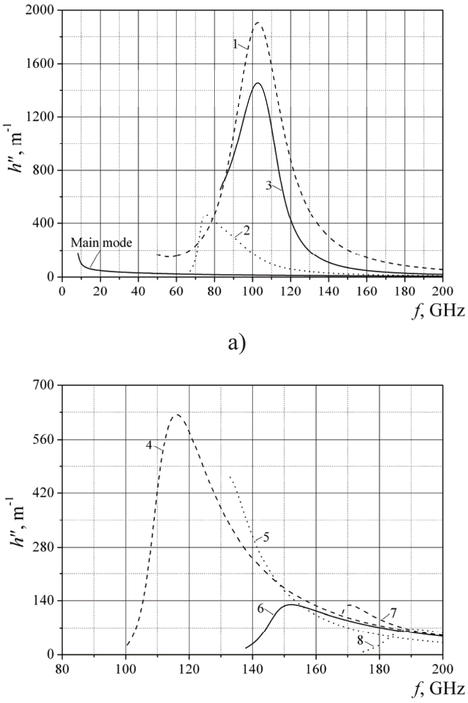


Fig. 5. Dependences of waveguide normalized phase constant on the frequency when the heavy holes' concentration is 90% of the total carrier concentration



a)

b)

Fig. 6. Dependences of waveguide loss on the frequency when heavy holes' concentration is 90% of total carrier concentration

In Figs 2, 4 and 6 are presented the waveguide losses. Loss graphs are separated in two parts for the larger clarity. In Figs 2a, 4a and 6a are shown the main and three higher mode losses. These modes are denoted by numbers 1, 2, 3. In Figs. 2b, 4b and 6b are shown other five higher modes' losses. The fourth higher mode is denoted by a number 4 and so on. In Figs 2a, 4a, 6a we see that the loss of the main mode are much lower than losses of all higher modes in the entire frequency range. It is important to note that the first higher mode loss is higher than the main mode loss for all value N_h. Initially the first mode loss grows till the maximum and then this loss slowly diminish with the growth of frequency. The maximum of the first higher mode loss is $h''_{max} = 190$ m^{-1} ($f = 77.0$ GHz) at the N_h equal to 10%, 379 m^{-1} ($f = 100.2$ GHz) at the N_h equal to 30%, 1907 m^{-1} ($f = 102.8$ GHz) at N_h equal to 90% of *N*.

We see that the maximum peak magnitude grows with the increasing of N_h. This behavior of the first higher mode loss points that this mode attenuates in the waveguide in a natural way. This means that the waveguide broadbandwidth additionally increases because of the sufficiently rapid attenuation of the first parasitic higher mode. The relation of the main mode loss at the specified frequencies of all range and the smallest loss of one of higher modes showed that the relation minimum is approximately equal to 2 ($f = 42$ and 200 GHz) and the maximum is 40 ($f = 102$ GHz) at $N_h/N = 0.3$. Similar relationships of losses are also observed with other percentages of the heavy holes.

Conclusions

1. In this work is utilized our new algorithm with our MATLAB software to examine of the phase and attenuation constants of dissipative epsilon- and (or) mu-gyrotropic rod waveguides. Our algorithm allows analyzing the very high losses (see Fig. 6a).
2. Here we present dependencies of dispersion characteristics of the magnetoactive *p*-Ge waveguide with two component hole charge carriers on the percentage of the heavy holes' concentration (Figs 1□6).
3. Here is shown that can be the degeneration and the transformation of the higher hybrid helicon modes (Figs 1 & 5).
4. We discovered that the main mode loss is very small and the maximum loss peak of the first higher mode grows with the increasing of the heavy holes' concentration (Figs 2a, 4a & 6a). It promotes the expansion of the waveguide broadbandwidth.

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In this work are examined the phase and attenuation constants of open magnetoactive p-Ge rod waveguides. Our algorithm allows analyzing the very high waveguide losses. Dispersion characteristics of p-Ge with two component hole charge carriers waveguide are calculated when the ratio of heavy holes' concentration in the material is equal to 10%, 30% and 90% of the total free carrier concentration. Dispersion characteristics of the main helicon and eight higher helicon modes are presented here. There are the degeneration and the transformation of higher hybrid modes at some heavy holes' concentrations. The waveguide broadbandwidth can be considerably extended due to the fact that the losses of the higher modes are considerably larger in comparisons to the main mode loss at the certain heavy holes' concentration. Ill. 6, bibl. 12 (in English; abstracts in English and Lithuanian).

L. Nickelson, A. Bubnelis, A. Baskys, R. Navickas. Atvirųjų cilindrinių girotropinių p-Ge bangolaidžių nuostolių priklausomybės nuo dviejų rūšių krūvininkų koncentracijos tyrimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 4(110). – P. 53–56.

Išnagrinėtos atvirųjų girotropinių skylinio laidumo germanio (p-Ge) bangolaidžių bangos tipų fazės ir slopinimo koeficientų priklausomybės nuo dviejų rūšių laisvųjų krūvininkų koncentracijos. Naudojamas algoritmas leidžia tirti bangolaidžius su labai dideliais nuostoliais medžiagoje. Apskaičiuotos p-Ge bangos tipų dispersinės charakteristikos, kai sunkiųjų skylučių koncentracija puslaidininkyje sudaro 10 %, 30 % ir 90 % visų laisvųjų krūvininkų koncentracijos. Pateiktos pagrindinio ir aštuonių aukštesniųjų bangos tipų helikoninių bangų dispersinės charakteristikos. Nustatyta, kad esant tam tikroms sunkiųjų skylučių koncentracijos vertėms aukštesniosios hibridinės modos gali transformuotis. Bangolaidžio plačiajuostiškumas gali būti gerokai išplėstas, atsižvelgiant į tai, kad aukštesniųjų bangos tipų nuostoliai yra kur kas didesni už pagrindinio bangos tipo nuostolius, esant tam tikroms sunkiųjų skylučių koncentracijoms. Il. 6, bibl. 12 (anglų kalba; santraukos anglų ir lietuvių k.).