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Dispersion Characteristics of the Propagation Waves in the Gyroelectric Semiconductor Waveguides

V. Mališauskas, D. Plonis
Department of Electronic Systems, Vilnius Gediminas Technical University,
Naugarduko str. 41-424, LT-03227 Vilnius, Lithuania, phone: +370 672 04450, e-mail: vacius.malisauskas@el.vgtu.lt

Introduction

In the microwave range there are used the simplest open cylindrical round cross-section waveguides of the semiconductor, ferrite and dielectric materials. They have a wide working frequency range and good electrodynamical characteristics [1].

Dielectric materials usually are used in microwave devices such as filters, coplanar waveguides, transmission lines [2–4].

Open cylindrical semiconductor and ferrite waveguides placed in the longitudinal magnetic fields are investigated in [5]. Also in some works semiconductor (plasma) waveguides their electrodynamical models and calculated dispersion and losses characteristics are presented. These research results are used for design and manufacture microwave devices [5–6].

In this paper dispersion characteristics and broadband width analysis of the cylindrical gyroelectrical n, p-InAs, n, p-InP waveguides are presented. These type semiconductor waveguides are investigated because they are rarely explored and their electrodynamical characteristics should be taken in account, designing microwave devices. Also in this article the original algorithm to calculate dispersion characteristics is presented.

Basic Theory of Semiconductor Waveguides

General electrodynamical model of the open cylindrical round cross-section gyrotropic waveguides in cylindrical coordinate $r,\ \varphi,\ z$ system is presented in the Fig. 1. It can be used for the analysis of semiconductor, gas discharge, ferrite, dielectrical and optical waveguides.

Area 1 in the model is in an external constant longitudinal magnetic field' $\boldsymbol{B}_0$, longitudinal exposed semiconductor (an upper index “s”) core – gyroelectric material, which can be described using complex permittivity tensor $\underline{\overleftrightarrow{\varepsilon}}_{\mathrm{r}}^{\mathrm{s}}$ and a real permeability $\mu_{\mathrm{r}}^{\mathrm{s}}=1$.

Model area 2, covers the core of the waveguide. It is external non-magnetic dielectric layer (an upper index “d”), characterized by the real relative permittivity $\varepsilon_{\mathrm{r}}^{\mathrm{d}}$ and the relative permeability $\mu_{\mathrm{r}}^{\mathrm{d}}=1$.

Third model area is the air which surrounds all waveguide model (an upper index “a”). Air permittivity and permeability are $\varepsilon_{\mathrm{r}}^{\mathrm{a}}=\mu_{\mathrm{r}}^{\mathrm{a}}\approx 1$.

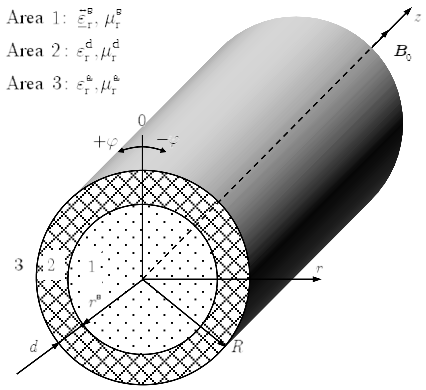

Fig. 1. General electrodynamical model of the open cylindrical round cross-section semiconductor waveguide: 1 is semiconductor core, 2 is external non-magnetic dielectric layer, 3 is air

General mathematical model of the gyroelectric semiconductor waveguides is presented below and in [5]. Semiconductor complex relative permittivity tensor is presented as

$$\underline{\overleftrightarrow{\varepsilon}}_{\mathrm{r}}^{\mathrm{s}}=\begin{vmatrix} \underline{\varepsilon}_{xx}^{\mathrm{s}} & i\underline{\varepsilon}_{xy}^{\mathrm{s}} & 0 \\ -i\underline{\varepsilon}_{xy}^{\mathrm{s}} & \underline{\varepsilon}_{xx}^{\mathrm{s}} & 0 \\ 0 & 0 & \underline{\varepsilon}_{zz}^{\mathrm{s}} \end{vmatrix}, \qquad (1)$$

where $\underline{\varepsilon}_{xx}^{\mathrm{s}}$, $\underline{\varepsilon}_{xy}^{\mathrm{s}}$, $\underline{\varepsilon}_{zz}^{\mathrm{s}}$ are the complex tensor elements.

The gyroelectric waveguides dispersion equations can be solved using Maxwell’s equations [1, 5]. The trancendentical linear dispersion equation system of the 8-th order determinant is expressed by $D^{\mathrm{s}}=\det[\underline{a}_{jk}]=0$.

Some non-zero complex determinant elements are presented as follows [5]:

$$\underline{a}_{46} = -N_m(\underline{k}_\perp^{\mathrm{d}} r^{\mathrm{s}}), \tag{2}$$

$$\underline{a}_{57} = -H_m^{(2)}(\underline{k}_\perp^{\mathrm{a}} R), \tag{3}$$

where m is hybrid waves first (azimuthal) index, describes longitudinal wave constant component by the azimuthal perimeter coordinate φ; $N_m(\underline{k}_\perp^{\mathrm{d}} r^{\mathrm{s}})$ is the Bessel function of the second kind of the m-th order with the complex argument $\underline{k}_\perp^{\mathrm{d}} r^{\mathrm{s}}$, where $\underline{k}_\perp^{\mathrm{d}}$ is the complex transversal wave constant (propagation coefficient) in the external dielectric layer; r^{s} is the radius of semiconductor waveguide core; $H_m^{(2)}(\underline{k}_\perp^{\mathrm{a}} R)$ is the Bessel function of the third kind m-th order with the complex argument $\underline{k}_\perp^{\mathrm{a}} R$, where $\underline{k}_\perp^{\mathrm{a}}$ is the complex outside transversal wave constant in the air; R is the external radius of open cylindrical waveguide.

Dispersion Characteristics Calculation Algorithm

The algorithm for the calculation of the propagation waves in the gyroelectric semiconductor waveguides in MATLAB® (Algorithm 1) consists of two stages – A and B.

Algorithm 1 Calculation of dispersion charateristics

A. Input parameters:

$\varepsilon_{\mathrm{r}}^{\mathrm{d}}, \varepsilon_{\mathrm{k}}^{\mathrm{s}\,n,p}, m, m^*, f_{\min}, f_{\max}, \Delta f, h'_{\min}, h'_{\max}, \Delta h',$

$B_0, \mu, N, R, r^{\mathrm{s}}.$

B. Evaluation of transcendental linear dispersion equation system.

for $f \leftarrow f_{\min}, \Delta f, f_{\max}$ **do**

1) Evaluation of the coefficients [5]:

$Re(\underline{\varepsilon}_{xx}^{\mathrm{s}}, \underline{\varepsilon}_{xy}^{\mathrm{s}}, \underline{\varepsilon}_{zz}^{\mathrm{s}}), \varepsilon_{\mathrm{ef}}, \mu_{\mathrm{ef}}, \underline{\Delta}_{\mathrm{S}}, k, \underline{k}_{\perp 1,2}^{\mathrm{s}},$

$\underline{k}_\perp^{\mathrm{a}}, \underline{k}_\perp^{\mathrm{d}}, \underline{a}, \underline{b}, \underline{s}_1, ..., \underline{s}_4, \underline{v}_1, ..., \underline{v}_4.$

2) Evaluation of the cylindrical functions:

$J_m(\underline{k}_\perp^{\mathrm{d}} r^{\mathrm{s}}), J'_m(\underline{k}_\perp^{\mathrm{d}} r^{\mathrm{s}}), N_m(\underline{k}_\perp^{\mathrm{d}} r^{\mathrm{s}}), N'_m(\underline{k}_\perp^{\mathrm{d}} r^{\mathrm{s}}),$

$N_m(\underline{k}_\perp^{\mathrm{d}} R), N'_m(\underline{k}_\perp^{\mathrm{d}} R), H_m^{(2)}(\underline{k}_\perp^{\mathrm{a}} R), H_m'^{(2)}(\underline{k}_\perp^{\mathrm{a}} R).$

3) Calculation of the determinant elements:

$\underline{a}_{jk}$ with $j = 0, 1, ..., 8$; and $k = 0, 1, ..., 8$.

4) Evaluation of the determinant: $D^{\mathrm{s}} = \det[\underline{a}_{jk}]$.

if $D^{\mathrm{s}} = 0$ then

write $h'r^{\mathrm{s}}$

write fr^{s}

$h'r^{\mathrm{s}}(fr^{\mathrm{s}})$

end if

end for

Initial analysis parameters are entered during stage A. The B stage of the Algorithm 1 consists of four steps: 1) evaluation of the coefficients; 2) evaluation of the cylindrical functions; 3) calculation of the determinant elements; 4) evaluation of the determinant.

For the determinant elements calculation there are used expressions presented in [5] and (2), (3) equations. Output results are the dependences of the normalized phase coefficient on the normalized frequency – $h'r^{\mathrm{s}}(fr^{\mathrm{s}})$.

Dispersion Characteristics Analysis

The calculated dispersion characteristics of the semiconductor n, p-InAs, n, p-InP waveguides are presented in Figs. 2–5. Semiconductor waveguides can be characterized using background dielectric constant; concentration, effective mass and mobility of the free carrier. Dispersion characteristics are calculated when total free carrier concentration is $N = 5 \cdot 10^{19}\ \mathrm{m}^{-3}$, it's the optimal concentration for n, p-InAs, n, p-InP semiconductor waveguides [7].

The analysis of the gyroelectric semiconductor n, p-InAs waveguides is performed by taking material background dielectric constant $\varepsilon_{\mathrm{k}}^{\mathrm{s}\,n,p} = 15.2$. Effective mass of the n-InAs semiconductor electrons is $m^* = 0.02 m_{\mathrm{e}}$ and mobility $\mu = 4\ \mathrm{m}^2/\mathrm{V \cdot s}$. p-InAs semiconductor waveguides holes effective mass is $m_\Sigma^* = 0.39 m_{\mathrm{e}}$ and mobility $\mu_\Sigma^* = 0.05\ \mathrm{m}^2/\mathrm{V \cdot s}$ [7]. Dispersion characteristics of the semiconductor n, p-InAs waveguides are presented in Figs. 2–3.

For these calculations the dielectric TM15 is used. The relative permittivity of selected dielectric is $\varepsilon_{\mathrm{r}}^{\mathrm{d}} = 15$ and relative (normalized) thickness is $d/r^{\mathrm{s}} = 0.3$ [5].

For the dispersion characteristics analysis waveguides normalized working frequencies range is Δfr^{s} (established as the difference between cutoff frequency of the first higher mode EH_{11} and cutoff frequency of the main mode HE_{11}) and broadband width – $\delta_f^{\mathrm{s}}, \%$ are used.

The broadband width of the waveguides is calculated using following expression [1, 5]

$$\delta_f^{\mathrm{s}} = \frac{\Delta fr^{\mathrm{s}}}{f_{\mathrm{c}} r^{\mathrm{s}}} \cdot 100,\ \% = \frac{2 \cdot (f_{\mathrm{cut1}} - f_{\mathrm{cut0}}) r^{\mathrm{s}}}{(f_{\mathrm{cut1}} + f_{\mathrm{cut0}}) r^{\mathrm{s}}},\ \% \tag{4}$$

where $f_{\mathrm{c}} r^{\mathrm{s}}$ is the normalized central waveguide working frequency.

It's seen in Fig. 2 that without external dielectric layer, the semiconductor n-InAs waveguides broadband width is $\delta_f^{\mathrm{s}}\Big|_{d/r^{\mathrm{s}}=0} = 56{,}5\ \%$. Semiconductor-dielectric waveguides broadband width decrease to $\delta_f^{\mathrm{s}}\Big|_{d/r^{\mathrm{s}}=0.3} = 53.3\ \%$.

It's shown in Fig. 3 that the semiconductor p-InAs waveguides, the broadband width is $\delta_f^{\mathrm{s}}\Big|_{d/r^{\mathrm{s}}=0} = 64{,}9\ \%$ with external dielectric layer waveguides broadband width decrease about $1\ \%$. This means that the cutoff frequencies of the waveguides $f_{\mathrm{cut1}} r^{\mathrm{s}}$ and $f_{\mathrm{cut0}} r^{\mathrm{s}}$ moves to lower frequencies.

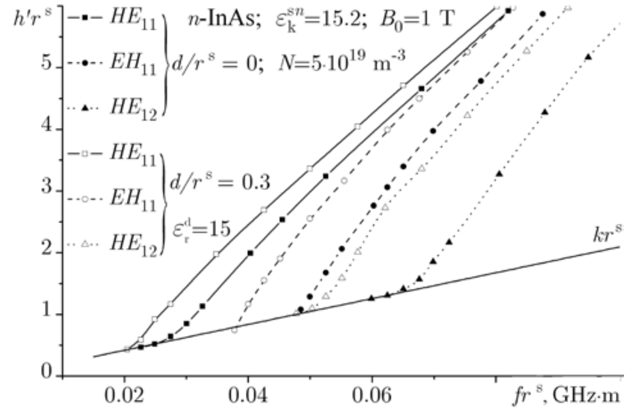

Fig. 2. Dispersion characteristics of the *n*-InAs semiconductor waveguides, when total electron concentration is $N = 5 \cdot 10^{19}\ \mathrm{m}^{-3}$ and external constant magnetic flux density is $B_0 = 1\ \mathrm{T}$

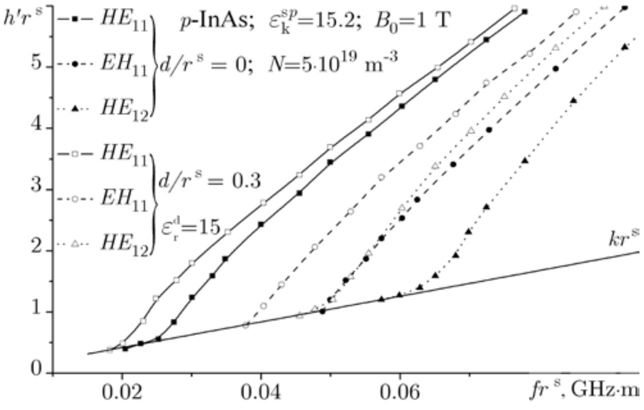

Fig. 3. Dispersion characteristics of the *p*-InAs semiconductor waveguides, when total hole concentration is $N = 5 \cdot 10^{19}\ \mathrm{m}^{-3}$ and external constant magnetic flux density is $B_0 = 1\ \mathrm{T}$

The n, p-InP semiconductor waveguides analysis is performed with material background dielectric constant $\varepsilon_{\mathrm{k}}^{\mathrm{s}\,n,p} = 12.5$.

Effective mass of the n type semiconductor electrons is $m^* = 0.08 m_{\mathrm{e}}$ with mobility $\mu = 5.40\ \mathrm{m}^2/\mathrm{V}\cdot\mathrm{s}$. p-InP semiconductor waveguides holes effective mass is $m_{\Sigma}^* = 0.58 m_{\mathrm{e}}$ and mobility $\mu_{\Sigma}^* = 0.02\ \mathrm{m}^2/\mathrm{V}\cdot\mathrm{s}$ [7].

Dispersion characteristics of the n, p-InP semiconductor waveguides are presented in Figs. 4–5. For the semiconductor n-InP waveguides without dielectric layer the cutoff frequency of main HE_{11} mode is $f_{\mathrm{cut0}} r^{\mathrm{s}}\Big|_{d/r^{\mathrm{s}}=0} = 0.039\ \mathrm{GHz}\cdot\mathrm{m}$. Waveguides broadband width is about $\delta_f^{\mathrm{s}}\Big|_{d/r^{\mathrm{s}}=0} = 34\ \%$, it's very small waveguides broadband width if waveguides used as phase shifters.

It's seen in Fig. 4 that with external dielectric layer semiconductor n-InP waveguides working frequencies range is $\Delta f r^{\mathrm{s}}\Big|_{d/r^{\mathrm{s}}=0.3} = 0.018\ \mathrm{GHz}\cdot\mathrm{m}$ and broadband width $\delta_f^{\mathrm{s}}\Big|_{d/r^{\mathrm{s}}=0.3} = 58\ \%$. The main mode HE_{11} and first higher mode EH_{11} cutoff frequencies moves to lover frequencies. With external dielectric layer semiconductor n-InP waveguides broadband width increases about $24\ \%$.

The other situation is with the p type InP semiconductor waveguides broadband width. With external dielectric layer waveguides broadband width decrease about $4.3\ \%$ (Fig. 5).

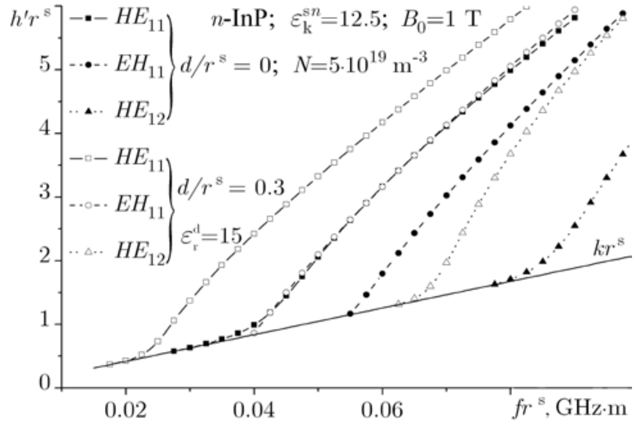

Fig. 4. Dispersion characteristics of the *n*-InP semiconductor waveguides, when total electron concentration is $N = 5 \cdot 10^{19}\ \mathrm{m}^{-3}$ and external constant magnetic flux density is $B_0 = 1\ \mathrm{T}$

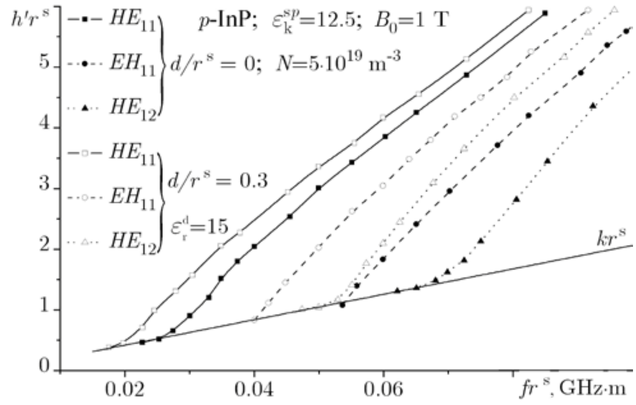

Fig. 5. Dispersion characteristics of the *p*-InP semiconductor waveguides, when total hole concentration is $N = 5 \cdot 10^{19}\ \mathrm{m}^{-3}$ and external constant magnetic flux density is $B_0 = 1\ \mathrm{T}$

The highest value of the broadband width for p-InP semiconductor waveguides is about $67.0\ \%$, without external dielectric layer and smallest broadband width is

n-InP semiconductor waveguides than p-InP semiconductor waveguides (Fig. 5).

The external dielectric layer can increase or decrease waveguides broadband width. This occurred because external dielectric layer changes electromagnetic field structure in semiconductor waveguide core.

In microwave devices like a phase shifters the semiconductor n, p-InAs, p-InP waveguides are more suitable, because of their wide working frequency range and high broadband width may change in the range of $\delta_f^s\Big|_{d/r^s=0,\ 0.3}=(53.3-67.0)\,\%$. Semiconductor n-InP waveguides broadband width without external dielectric layer is smaller. It means that working frequency range is narrow. So for phase shifters the semiconductor n, p-InAs, p-InP waveguides are preferable.

Conclusions

The algorithm and program for dispersion characteristics calculations and analysis in MATLAB® is developed and results of calculations are analyzed.

External dielectric layer always changes cutoff frequencies of the main mode and first higher mode.

The external dielectric layer of the waveguide changes working frequency range and broadband width because external dielectric layer changes electromagnetic field structure in semiconductor waveguides core.

In microwave devices the use of n, p-InAs, p-InP semiconductor waveguides is preferable. The electrodynamical parameters of the n, p-InAs, p-InP semiconductor waveguides are better and they have wide working frequency range, than semiconductor n-InP waveguides.

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Presented general electrodynamical and mathematical model of the open cylindrical round cross-section gyroelectric semiconductor waveguides. Created general algorithm and program in MATLAB® for calculations dispersion characteristics of the propagation wave's in the waveguides. Are investigated characteristics of the waves HE_{11}, EH_{11} and HE_{12} in 0.01– 0.1 GHz·m normalized frequency range. The waves propagated in *n*, *p*-InAs, *n*, *p*-InP semiconductor and semiconductor-dielectric waveguides, and they are in an external constant longitudinal magnetic flux density 1 T. Waveguide parameters established: working frequency range, central frequency and broadband width. Ill. 5, bibl. 7 (in English; abstracts in English and Lithuanian).

V. Mališauskas, D. Plonis. Giroelektriniais puslaidininkiniais bangolaidžiais sklindančių bangų dispersinės charakteristikos // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2010. – Nr. 10(106). – P. 87–90.

Pristatomi bendrieji elektrodinaminis ir matematinis atvirųjų cilindrinių apskritojo skerspjūvio giroelektrinių puslaidininkinių bangolaidžių modeliai. Sukuriami bendrieji algoritmas ir programa MATLAB® terpėje šiais bangolaidžiais sklindančių bangų dispersinėms charakteristikoms apskaičiuoti. Tiriamos bangų HE_{11}, EH_{11} ir HE_{12} charakteristikos 0,01– 0,1 GHz·m normuotųjų dažnių ruože. Bangos sklinda *n*, *p*-InAs, *n*, *p*-InP puslaidininkiniuose ir puslaidininkiniuose-dielektriniuose bangolaidžiuose, kuriuos išilgai veikia 1 T pastovusis magnetinis srautas. Nustatomi bangolaidžių parametrai: darbo dažnių juosta, centrinis dažnis ir plačiajuostiškumas. Il. 5, bibl. 7 (anglų kalba; santraukos anglų ir lietuvių k.).