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The Investigation of Gyroelectric *n*-InAs Phase Shifters Characteristics

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Introduction

The microwave phase shifters can be manufactured using microstrip lines and open cylindrical waveguides [1]. The propagation and attenuation of phase wave's characteristics may vary in ferrite and semiconductor waveguides by changing longitudinal magnetic flux density, external dielectric layer width and permittivity of dielectric layer, semiconductor temperature, the concentration of the free charge carriers.

Nowadays the investigation of the semiconductor and semiconductor-dielectric waveguides is very relevant and important for the sake of science. The usage and possibilities of latter mentioned waveguides in gyroelectric phase shifters are not known [2–4].

n-InAs semiconductor has been selected for the purpose of investigation. The super high frequency transistors are manufactured using *n*-InAs semiconductors, which have the higher concentration of electrons.

The influence of external dielectric layer on the parameters of gyroelectric *n*-InAs semiconductor and semiconductor-dielectric phase shifters has been hardly investigated in this paper. The aim is to maximize the differential phase shift module at a relatively low concentration of electrons.

The dispersion, phase and attenuation characteristics of the phase shifters are investigated, when the main type hybrid mode HE_{11} propagates in phase shifters.

Structure of phase shifter

General structure of the open cylindrical gyroelectric phase shifter in coordinate r, φ, z system is presented in the Fig. 1.

In the structure (Fig. 1), area 1 is exposed by a constant longitudinal magnetic field, which is defined as a magnetic flux density vector $\boldsymbol{B}_0$. It is the semiconductor (an upper index "s") core – gyroelectric material, which can be described by using complex permittivity tensor $\vec{\underline{\varepsilon}}_r^{\,s}$ and a real relative permeability $\mu_r^s = 1$.

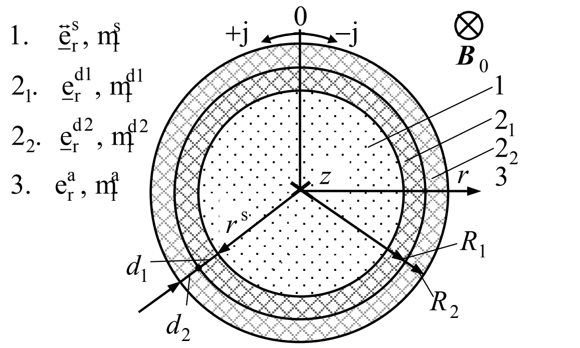

Fig. 1. Structure of the gyroelectric open cylindrical phase shifter with two dielectric layers: 1 – semiconductor core, 2_1 and 2_2 – external non-magnetic dielectric layers, 3 – air

The structure area 2, consists of two (area 2_1 and 2_2) external non-magnetic dielectric layers complex relative permittivities $\underline{\varepsilon}_r^{d1}$, $\underline{\varepsilon}_r^{d2}$ and the permeability $\mu_r^{d1,2} = 1$.

Third area of the structure is the air which surrounds the whole structure of phase shifter (an upper index "a").

Maxwell complex differential equations and boundary condition method are used to obtain the complex dispersion equation.

Dispersion and phase characteristics calculation algorithm and results of the analysis are presented in the article [5].

Attenuation calculation algorithm

The attenuation calculation algorithm of gyroelectric phase shifters, consists of three stages. Initial analysis parameters and frequency $[f_{\min}^{it}\ f_{\max}^{it}]$, and phase constant $[h'^{it}_{\min}\ h'^{it}_{\max}]$ (*it* is the number of iterations) values are entered during the stage A. The frequency and phase constant values are calculated using in [5] presented algorithm. The complex dispersion equation is evaluated during the stage B. The complex propagation constant $\underline{h} = h' - ih''$ (here h' is the phase constant, h'' is the attenuation coefficient) is found at the stage C.

Algorithm. Attenuation calculation algorithm

A. Initialization of system parameters.

$\underline{\varepsilon}_r^{d1}$, $\underline{\varepsilon}_r^{d2}$, ε_k^{sn}, m, m^*, $[f_{\min}^{it}\ f_{\max}^{it}]$, $[h'^{it}_{\min}\ h'^{it}_{\max}]$,

B_0, μ, N, R_1, R_2, ρ^s.

B. Solving transcendental linear dispersion equation system.

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

1) Calculation of the relative complex permittivity tensor.
2) Calculation of the coefficients [4]:

   for $h''^{ith''} \leftarrow h''^{ith''}_{\min}, \Delta h'', h''^{ith''}_{\max}$ **do**

   $\underline{h} = h'^{it} - \mathrm{i}h''^{ith''}$;

   ε_{ef}, μ_{ef}, $\underline{\Delta}_{PF}$, k, $\underline{k}_{\perp 1}^{s}$, $\underline{k}_{\perp 2}^{s}$, $\underline{k}_{\perp}^{a}$, $\underline{k}_{\perp}^{d}$,

   $\underline{a}$, $\underline{b}$, $\underline{s}_1$, ..., $\underline{s}_4$, $\underline{v}_1$, ..., $\underline{v}_4$.
3) Calculation of the cylindrical functions.
4) Calculation of the determinant elements:

   $\underline{a}_{jk}$, when $j = 0, 1, ..., 12$ and $k = 0, 1, ..., 12$.
5) Evaluation of the determinant $\left|\underline{D}\right|^{s,d} = \det(\underline{a}_{jk})$.
6) Saving determinant values $\left|\underline{D}\right|^{s,d}_{ith'',\ it}$.

   end for

end for

C. The complex wave propagation constant $\underline{h} = h' - \mathrm{i}h''$ evaluation.

for $it \leftarrow 0, 1, \left\|[f_{\min}^{it}\ f_{\max}^{it}]\right\|$ **do**

for $ith'' \leftarrow 0, 1, \left\|h''^{ith''}\right\| - 1$ **do**

if $\left|\underline{D}\right|^{s,d}_{ith''-1,\ it} > \left|\underline{D}\right|^{s,d}_{ith'',\ it}$ **and** $\left|\underline{D}\right|^{s,d}_{ith''+1,\ it} > \left|\underline{D}\right|^{s,d}_{ith'',\ it}$

$\underline{h} = h'^{it} - \mathrm{i}h''^{ith''}$;

$h'\rho^s(f\rho^s)$.

end if

end for

end for

Investigation of *n*-InAs phase shifters with two external dielectric layers

Gyroelectric phase shifters dispersion characteristics are presented as normalized phase constant $h'\rho^s$ dependences on the normalized frequency $f\rho^s$. The polarization of the hybrid modes is left-hand ($e^{+\mathrm{i}m\varphi}$).

The investigation of the *n*-InAs semiconductor and semiconductor-dielectric phase shifters is performed by taking electron mobility $\mu = 4\ \mathrm{m}^2/\mathrm{V\cdot s}$, effective mass $m^* = 0.02m_e$ (m_e – is mass of free carrier) and material background constant $\varepsilon_k^{sn} = 15.2$ [6].

The dispersion characteristics of the phase shifters, without external dielectric layer $d_{1,2}/\rho^s = 0$ is presented in paper [5], when concentration $N = 5\cdot 10^{19}\ \mathrm{m}^{-3}$.

The main mode HE_{11} dispersion characteristics of the *n*-InAs semiconductor-dielectric phase shifters are shown in the Fig. 2, when the concentration of electrons is small $N = 1\cdot 10^{19}\ \mathrm{m}^{-3}$ and magnetic flux density is varied $B_0 = 0, 0.25, 0.5, 0.75, 1$ T, also only one external dielectric layer is used.

For external dielectric layer TM-15 type dielectric is used [4]. The external dielectric layer relative complex permittivity is $\underline{\varepsilon}_r^{d1,2} = 15(1 - \mathrm{i}\cdot 10^{-4})$ and the relative thickness of dielectric layer is $d_{1,2}/\rho^s = 0.15$.

On the basis of dispersion characteristics (Fig. 2), it can be seen that, when we change magnetic flux density B_0, the main mode HE_{11} phase constant also changes at normalized frequency $f\rho^s = 0.0325\ \mathrm{GHz\cdot m}$, which is in working frequency range $\Delta f\rho^s = 0.018\ \mathrm{GHz\cdot m}$ and here we have a phase shift.

In Fig. 3, the mode HE_{11} dispersion characteristics is presented, when normalized dielectric layer thickness is $d_{1,2}/\rho^s = 0.15$. The first dielectric layer relative permittivity is a equal to air $\varepsilon_r^{d1} = 1$, and the second dielectric layer permittivity is $\underline{\varepsilon}_r^{d2} = 15(1 - \mathrm{i}\cdot 10^{-4})$.

Comparing Fig. 2 and Fig. 3, it can be seen that the cut-off frequencies of the main mode HE_{11} move to higher frequencies. When we change external dielectric layer width and permittivities.

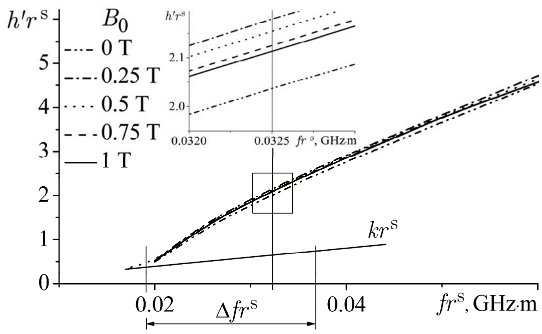

Fig. 2. Dispersion characteristics of the *n*-InAs phase shifter, when $N = 1\cdot 10^{19}\ \mathrm{m}^{-3}$, $d_{1,2}/\rho^s = 0.15$, $\underline{\varepsilon}_r^{d1,2} = 15(1 - \mathrm{i}\cdot 10^{-4})$

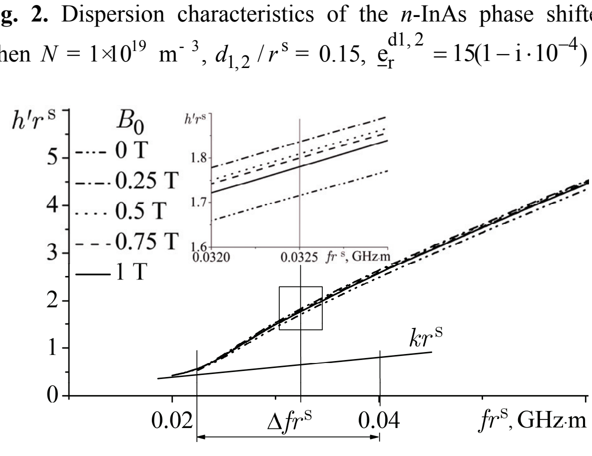

Fig. 3. Dispersion characteristics of modes HE_{11} of the *n*-InAs phase shifter, when $N = 1\cdot 10^{19}\ \mathrm{m}^{-3}$, $d_1/\rho^s = 0.15$, $\varepsilon_r^{d1} = 1$ and $d_2/\rho^s = 0.15$, $\underline{\varepsilon}_r^{d2} = 15(1 - \mathrm{i}\cdot 10^{-4})$

Differential phase shift module $|\Delta\vartheta|\big|_{fr^{s}=\mathrm{const}}$ dependence on the magnetic flux density B_0 can be obtained using dispersion characteristics of the phase shifters. It can be calculated by drawing a vertical line in the phase shifter working frequency range Δfr^{s}, for example at the normalized frequency $fr^{s} = 0.0325$ GHz·m. The vertical lines are drawn in Fig. 2 and Fig. 3.

Differential phase shift module in degrees can be obtained using equation [4]

$$|\Delta\vartheta|\big|_{fr^{s}=\mathrm{const}} = \left|\left(h_0' r^{s} - h_{B_0}' r^{s}\right)/r^{s}\right| \cdot L \cdot 360/2\pi \ ^\circ, \qquad (1)$$

where $h_0' r^{s}$ is the normalized phase constant, when $B_0 = 0$ T; $h_{B_0}' r^{s}$ is the normalized phase constant, when $B_0 \neq 0$ T; L is the length of the phase shifter.

In Fig. 4, the differential phase shift module dependences on the magnetic flux density is presented. From Fig. 4, it is seen that the phase shifters have wide working range without external dielectric layer $d_{1,2}/r^{s} = 0$ and with it $d_{1,2}/r^{s} = 0.15$, $\underline{\varepsilon}_r^{d1,2} = 15(1 - i \cdot 10^{-4})$.

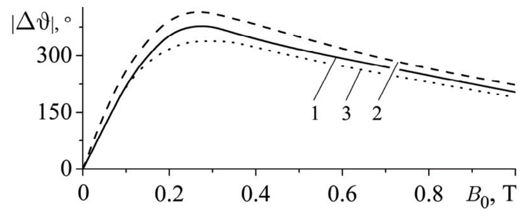

Fig. 4. The differential phase shift module dependences on the magnetic flux density, where $1 - d_{1,2}/r^{s} = 0$; $2 - d_{1,2}/r^{s} = 0.15$, $\underline{\varepsilon}_r^{d1,2} = 15(1 - i \cdot 10^{-4})$; $3 - d_1/r^{s} = 0.15$, $\varepsilon_r^{d1} = 1$, $d_2/r^{s} = 0.15$, $\underline{\varepsilon}_r^{d2} = 15(1 - i \cdot 10^{-4})$

The widest working range of the *n*-InAs phase shifters can be obtained, when the magnetic flux density B_0 is varied from 0 to 0.25 T. Then the maximum is obtained with external dielectric layer and without it, for example when phase shifter core length is $L = 50$ mm.

Referring to the characteristics shown in Fig. 4, it can be noticed that, the external dielectric layer, when relative thickness is $d_{1,2}/r^{s} = 0.15$ and permittivity $\underline{\varepsilon}_r^{d1,2} = 15(1 - i \cdot 10^{-4})$, expands the conversion range of phase shifters and reinforce quite thin and fragile phase shifters cores. Also the external dielectric layer decreases attenuation of electromagnetic (EM) waves in phase shifters, because the highest EM wave attenuation can be obtained without external dielectric layer $d_{1,2}/r^{s} = 0$.

With external dielectric layer which relative permittivity is equal to air, $|\Delta\vartheta|\big|_{fr^{s}=\mathrm{const}}$ is less than 400°, it means that the dielectric layer with $\varepsilon_r^{d} = 1$ reduces the phase shifter conversion range.

The lower concentration of electrons $N = 1 \times 10^{19}$ m^{-3} is taken in our calculations, so that the *n*-InAs semiconductor-dielectric phase shifters would not work as a wave absorber.

The highest attenuation of main mode HE_{11} propagated in semiconductor *n*-InAs phase shifters can be obtained without external dielectric layer ($d_{1,2}/r^{s} = 0$). The attenuation characteristics are presented in Fig. 5.

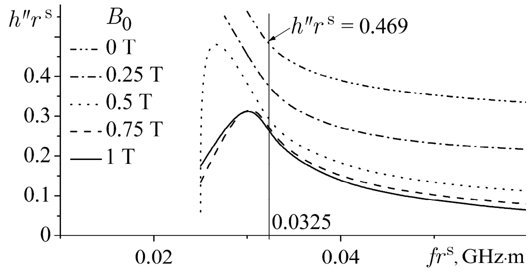

Fig. 5. Attenuation characteristics of modes HE_{11} of the *n*-InAs phase shifter, when $N = 1 \times 10^{19}$ m^{-3}, $d_{1,2}/r^{s} = 0$

Attenuation characteristics of the *n*-InAs semiconductor-dielectric phase shifters at different magnetic flux densities B_0 are shown in Fig. 6. These characteristics show that EM wave attenuation in *n*-InAs phase shifters increases, when B_0 decreases. It is seen here that the attenuation coefficient decreases after the main mode cut-off frequency $f_{\mathrm{cut}0} r^{s} = 0.0193$ GHz×m and the attenuation stabilizes after frequency $fr^{s} = 0.0325$ GHz·m at $B_0 = 0$ and $B_0 = 0.25$ T. This phenomenon can be explained by diagrams, shown in Fig. 7.

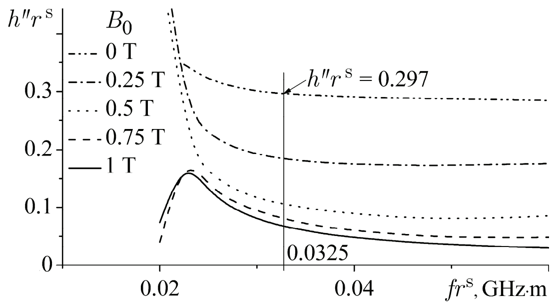

Fig. 6. Attenuation characteristics of the *n*-InAs phase shifter, when $N = 1 \times 10^{19}$ m^{-3}, $d_{1,2}/r^{s} = 0.15$, $\underline{\varepsilon}_r^{d1,2} = 15(1 - i \cdot 10^{-4})$

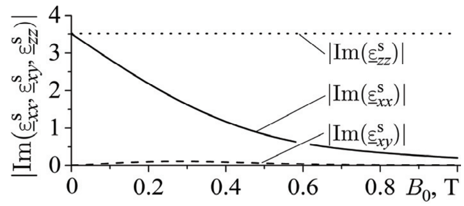

Fig. 7. $\left|\mathrm{Im}(\underline{\varepsilon}_{xx}^{s}, \underline{\varepsilon}_{xy}^{s}, \underline{\varepsilon}_{zz}^{s})\right|$ dependences on magnetic flux density B_0, when $N = 1 \times 10^{19}$ m^{-3}, $fr^{s} = 0.0325$ GHz×m

The imaginary parts $\left|\mathrm{Im}(\underline{\varepsilon}_{xx}^{s}, \underline{\varepsilon}_{zz}^{s})\right|$ of the complex relative permittivity tensor of the n-InAs core Fig. 7 coincide, when $B_0 = 0$ T, and $\left|\mathrm{Im}(\underline{\varepsilon}^{s}_{xy})\right|$ value is equal to zero, when $B_0 = 0$ T. In this case the n-InAs semiconductor-dielectric phase shifter transforms into layered dielectric waveguide.

It is shown in Fig. 8 that attenuation coefficient of mode HE_{11} decreases after cut-off frequency $f_{\mathrm{cut}0} r^{s}$ = 0.0225 GHz×m. The mode (wave) attenuation increases, when between the semiconductor core and the dielectric there is an air space. It means that the electromagnetic waves are more concentrated in semiconductor core, so the mode attenuation increases more than using one external dielectric layer $d_{1,2}/r^{s}$ = 0.15 (Fig. 6). The electromagnetic field concentrates more in the dielectric layer than in the air. The lower attenuation is in air and higher in dielectric layer.

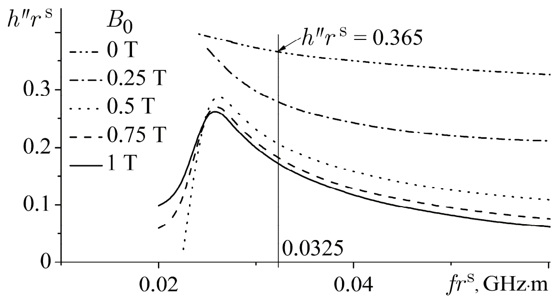

Fig. 8. Attenuation characteristics of modes HE_{11} of the n-InAs phase shifter, when $N = 1\times10^{19}$ m^{-3}, $d_1/r^{s} = 0.15$, $\varepsilon^{d1}_{r} = 1$ and $d_2/r^{s} = 0.15$, $\underline{\varepsilon}^{d2}_{r} = 15(1 - i\cdot10^{-4})$

The attenuation characteristics shown in Fig. 8 reveal, that the attenuation maximum at the main mode HE_{11} cut-off frequency increases approximately by 1.5 times, when B_0 is varied from 0 to 1 T. The high EM wave attenuation is undesirable because it reduces the transmission of EM wave power.

Conclusions

In this paper open cylindrical gyroelectric semiconductor phase shifters with core without dielectric layer and with one and two dielectric layers are investigated.

The highest n-InAs semiconductor and semiconductor-dielectric phase shifters $|\Delta\vartheta|_{fr^{s}=\mathrm{const}}$ can be obtained, when B_0 are from 0 to 0.25 T.

The attenuation in the phase shifters with one external dielectric layer with $\underline{\varepsilon}^{d1,2}_{r} = 15(1 - i\cdot10^{-4})$, is the lowest, it means that the EM waves are more concentrated in the external dielectric layer than in the gyroelectric core.

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In this paper the open cylindrical gyroelectric phase shifters characteristics are investigated. The investigation is performed by changing their parameters: the magnetic flux density, the number of layers of dielectric, width and permittivities. The highest differential phase shift in n-InAs semiconductor and semiconductor-dielectric phase shifters can be obtained in range of magnetic flux density from 0 to 0.25 T. The minimum attenuation in phase shifters is obtained with one external dielectric layer. Ill. 8, bibl. 6 (in English; abstracts in English and Lithuanian).

V. Mališauskas, D. Plonis. Giroelektrinių *n*-InAs fazės keitiklių charakteristikų tyrimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2012. – Nr. 6(122). – P. 121–124.

Straipsnyje tiriamos atvirųjų cilindrinių giroelektrinių fazės keitiklių charakteristikos, keičiant jų parametrus: magnetinio srauto tankį, dielektrikų sluoksnių skaičių, storius ir dielektrines skvarbas. Nustatyta, kad n-InAs puslaidininkiniuose ir puslaidininkiniuose-dielektriniuose fazės keitikliuose didžiausias diferencinis fazės pokytis gaunamas, kai magnetinio srauto tankis yra nuo 0 iki 0,25 T. Mažiausiai elektromagnetinės bangos slopinamos keitikliuose su vienu išorinio dielektriko sluoksniu. Il. 8, bibl. 6 (anglų kalba; santraukos anglų ir lietuvių k.).