

Non-reciprocal passive protection of HF transmitters from reflection failure by the help of semiconductor isolators

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Abstract. *The fundamental problem of protection the transmitters against microwave energy reflections from aircraft antenna is discussed. The paper presents some applications of active and passive isolators and circulators as a tool for protection reflections. It has been stated that electrical properties of ferrite isolators an circulators grow worse at lower operational frequencies (below 50 MHz) and temperatures (cryogenic). Semiconductor magnetoplasma exhibits gyrotropic effects similar to those of magnetized ferrites and can solve the problem non-reciprocity in the HF range from 3 to 30 MHz, which is important for HF communication. The semiconductors devices realization, optimal parameters, operational temperature range, based on minimum forward loss α and maximum reverse attenuation β , were chosen. Major electromagnetic parameters of semiconductor isolators were determined.*

1. Introduction

Ferrite circulators and isolators are the key elements in modern microwave engineering. Their fundamental property of non-reciprocity is capable of simplifying the construction and improving the stability, efficiency and accuracy of radar, communication and testing systems.

An isolator is a passive non-reciprocal 2-port device which permits signal energy to pass through it in forward direction whilst absorbing energy in the reverse direction.

A circulator is a passive non-reciprocal device with 3 or more ports. Energy introduced into first port is transferred to second port, the others ports being isolated.

The frequency range within the non-reciprocal ferrite devices meets the guaranteed specifications is no less 50 MHz.

Non-reciprocal devices placed between the transmitter and antenna. RF signal can reach the antenna but returning signal goes to the load (circulator) or dissipating at the core (isolator).

Insertion loss α (expressed in dB) is the attenuation that results from including the device. It is also defined as the ratio of signal power at the output of the inserted device to the signal power at the input of the inserted device.

Isolation β is the ratio, expressed in dB of the input power to output power for signal in the reverse direction.

Maximum power and temperature range are the same important parameters for the non-reciprocal devices.

Electrical properties of ferrite isolators and circulators grow worse at lower operational frequencies (below 50 MHz) and temperatures (cryogenic).

Semiconductor magnetoplasma exhibits gyrotropic effects similar to those of magnetized ferrites and can solve the problem non-reciprocity in the HF range from 3 to 30 MHz, which is important for HF communication [1].

A different approach to the basic nonreciprocal mechanism is used in solid-state plasma devices. This approach makes use of solid-state plasma waves, so-called helicon waves which are nonreciprocal by their nature [2].

An active isolator the same can solve the protection problems [3]. The active devices have noise, input and output, linearity problems, but they are useful solution over wide bandwidths, where ferrite and semiconductor isolators are unavailable.

2. Physical background of investigation

Physical background of the operation of semiconductor isolator is based on the effect of the dimensional resonance of helicon waves in plate placed in the static magnetic field.

The propagation of magnetoplasma wave k_{\pm} may be detected from the characteristic equation [4].

$$c^2 k_{\pm}^2 = \frac{\omega_p^2 \omega}{\pm \omega_H + i\tau^{-1}}, \quad \omega_p^2 = \frac{4\pi Ne^2}{m}, \quad (1)$$

$$\omega_H = \frac{eH}{mc}.$$

where k is wave vector, ω is frequency, ω_H is cyclotron frequency, ω_p is plasmas frequency, H is magnetic field, τ is relaxation time and m is effective mass carries. The items with the argument k_+ are caused by the helicon waves. In the case $\omega_H\tau \gg 1$ we have

$$k_+ = \sqrt{\frac{\omega_p^2 \cdot \omega}{\omega_H \cdot c^2} \left(1 - \frac{i}{\omega_H \tau} \right)}. \quad (2)$$

And effective magnetic permeability

$$\mu_{eff} = \frac{\Phi_x}{2aH} = \frac{tg_- a}{2k_- a} + \frac{tg_+ a}{2k_+ a}. \quad (3)$$

The μ_{eff} has maximum in the case of resonance

$$(\text{Re } k_+)a = \frac{n\pi}{2}, \quad n=1,3,5,\dots \quad (4)$$

3. Modeling of the semiconductor isolators

We have developed a model of the helicon isolator. We considered the electromagnetic parameters of the helicon resonator material, dimensional effects, the impact of the mine carriers, and some other issues.

The main element of the model represented is the nonreciprocal transformer, characterized by the matrix of impedances.

The impedance matrix for the nonreciprocal transformer is calculated according to the formula [5].

$$|Z| = \begin{vmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{vmatrix} = \begin{vmatrix} i\omega L_1 & i\omega M_{21} \\ i\omega M_{12} & i\omega L_2 \end{vmatrix}, \quad (5)$$

where $L_1 = \mu_L L_{01}$ and $L_2 = \mu_L L_{02}$ are inductances of coils whose physical dimensions are approximately the same as helicon resonator size $M_{21} = -M_{12} = M_L \mu_T$, $M_L^2 = L_{01} L_{02}$.

μ_L and μ_T are „magnetic permeabilities“ of semiconductor core in parallel and perpendicular directions, when resonance ($n = 1$) appear

$$\mu_L = 1 - 4/\pi^2 (1 + 2iQx_m) / [1 + iQ(x_m - x_m^{-1})], \quad (6)$$

$$\mu_T = 4u/\pi^2 (1 / [1 + iQ(x_m - x_m^{-1})]), \quad (7)$$

where $u = R_H |B| / \rho = \text{tg}\Theta$, Θ are the Hall angle and R_H is the Hall constant.

Quality of the helicon resonator depends on the Hall constant and magnetic induction B

$$Q = 1/2 (1 + u^2)^{1/2}. \quad (8)$$

The angular frequency of the mine dimensional resonance (resonance Fabry-Perot) $\omega_r(0)$

$$\omega_r(0) = (2\rho Q/\mu_0)(\pi^2/d^2). \quad (9)$$

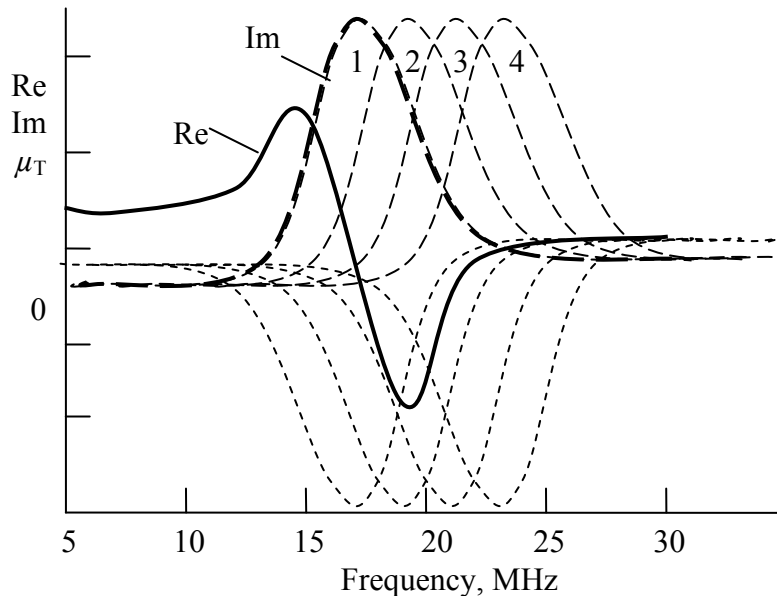


Fig. 1. Calculated frequency responses of magnetic permeability μ_T of a nonreciprocal transformer.

If $u = \mu B > l$, $\omega_r(0) \ll \omega_H$, where μ is carrier mobility, the frequency of the mine dimension resonance can be written in simple form [5],

$$f_r = AB / (Nd^2), \quad (10)$$

where $A = 7,82 \cdot 10^{24}$ is the constant, N is density (concentration) of the carrier of the semiconductor material.

The quadripole of this type will resemble a gyrator. The half wave helicon resonator with the inductance coils represents passive device - the nonreciprocal transformer with nonreciprocal phase shift equal to 180° in the direct ($+\pi/2$) and reverse ($-\pi/2$) directions.

The rate of coupling between the inductance coils and the resonator depends on Q factor of the dimensional resonator, number of turns in the inductance coils, on the filling of coils by core, and the cross section between the coils [5].

By transmitting the helicon waves through a semiconductor plate the effect of a resonator shape and size on resonance characteristics was investigated. It was found that $d/a < 0.2$, where a is the least value of the plate with, resonance frequency may be determined by the equation (10), used for semi – infinite resonator.

In Fig. 1 we can see calculated by (7) the frequency responses of the real and imaginary parts of the magnetic permeability μ_T of a semiconductor core - helicon resonator. The curves 1, 2, 3, 4 cover different electrons densities N of semiconductor: $2,3 \cdot 10^{-22} \text{ m}^{-3}$ (4); $2,0 \cdot 10^{-22} \text{ m}^{-3}$ (3); $1,7 \cdot 10^{-22} \text{ m}^{-3}$ (2); $1,4 \cdot 10^{-22} \text{ m}^{-3}$ (1).

On Fig. 2 typical dependences of the Hall constant R_H of n-InSb, doped with tellurium, on temperature are shown. We can see, that only for doped n-InSb (density donors $N_D = 1,0 \cdot 10^{23} \text{ m}^{-3}$) in temperatures $T \sim 300\text{K}$ the Hall constant R_H and density N are stable. For doped n-InSb (density donors $N_D = 1,3 \cdot 10^{22} \text{ m}^{-3}$) stable range of R_H do not exceed 250 K.

If mine carriers (electrons) density $N > 2 \cdot 10^{-23} \text{ m}^{-3}$, ($T = 300\text{K}$), the temperature stability is better, but mobility of electrons (Fig. 2) are less $4 \text{ m}^2\text{V}^{-1}\text{s}^{-1}$. High magnetic fields are necessary.

We can supplement nonreciprocal phase transformer with new circuit elements depends on the schematic realization of the isolator as nonreciprocal LC-filters different types. The isolators (Fig. 3) can be made-up with nonreciprocal low pas filter (L1-C2-L2), nonreciprocal high pas filter (L1-C4-L2) or with band pass or band rejection filters [7, 8].

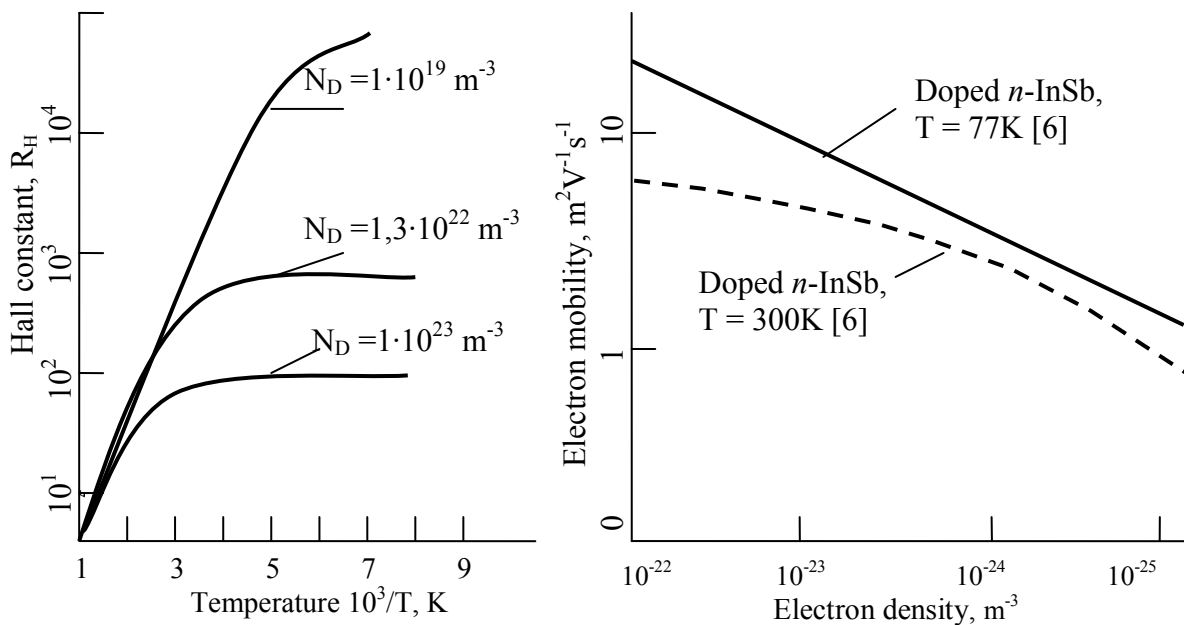


Fig. 2 Dependences of the Hall constant R_H of n-InSb, doped with tellurium, on temperature and electron mobility μ on density N of doped n-InSb.

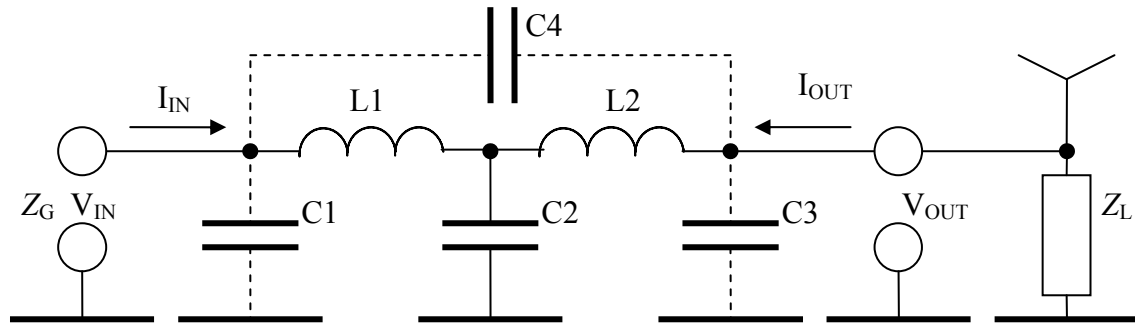


Fig. 3. Semiconductor isolator

The scattering matrix for the isolator:

$$|S| = \begin{vmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{vmatrix} = \begin{vmatrix} 0 & Ue^{i\zeta} \\ 0 & 0 \end{vmatrix}, \quad (11)$$

where U is invariant of the isolator system and for ideal isolator $U = 1$, because insertion loss $\alpha = 0$.

For the nonreciprocal low pass filter (L1-C2-L2) isolator $U^2 = 1 / (1 + 1/u^2)$. The electrical parameters of the circuit components (for example the capacitance C2) can be found by minimum loss α .

We can calculate direct loss α and reverse attenuation β in decibel by the formula.

$$\alpha, \beta = 10 \lg(\text{Re}P_L / \text{Re}P_G) = 10 \lg \{ |Z_{IN}| \text{Re}Z_L / [|Z_T| (Z_{IN} - Z_G)] \}, \quad (12)$$

where P_G , Z_G are power and impedance of the generator, P_L is output power and, Z_L is load impedances and $Z_{IN} = V_{IN}/I_{IN}$; $Z_T = V_{IN}/I_{OUT}$.

4. Problem of temperature stability. Choice and optimization of the material

According to (10) the density of carrier should be temperature stable. The most appropriate semiconductor is the n -type indium antimony (n -InSb) doped with tellurium. If there are higher the electron density the temperature stability better. However, an increase in concentration of donor impurity results in diminishing the electrons mobility and in the resonator quality factor. All this will cause the isolator forward loss to increase. The temperature characteristics of helicon resonators were considered for a low-band filter isolators because loss of these isolators is lower.

Based on the chosen model, we have calculated the main characteristics of the isolator: direct loss α and reverse attenuation β in the wide range of temperatures and frequencies. It has been shown that for the development of mobile non-reciprocal devices a semiconductor material of high carrier mobility $\mu > 4 \text{ m}^2\text{V}^{-1}\text{s}^{-1}$ and high mine carrier density $N > 10^{22} \text{ m}^{-3}$, ($T = 300\text{K}$), is needed. The electrical parameters of semiconductors should be stable in operational temperature range. Te – doped n -InSb, semiconductor alloy $\text{Cd}_x\text{Hg}_{1-x}\text{Te}$ ($x \sim 0,1$) and anisotropic alloy $\text{Bi}_{1-x}\text{Sb}_x$ ($x \sim 0,1$) offers valuable properties.

In our calculations, we considered the frequency responses and temperature characteristics of the helicon resonator material, the helicon resonator geometry, physical parameters and dimensions of the inductance coils, characteristics of insulation between the coils, parameters of the transformer filling, electrical parameters of the circuit components, etc.

5. Conclusions

Nonreciprocal passive devices as isolators and circulator based on ferrite medium are used in microwave engineering and wireless communication. One of the problems is protection the transmitters against microwave energy reflections from aircraft antenna in decametric range of waves. The low-frequency limit of applicability of ferrite nonreciprocal devices is 50 MHz. At lower frequency range, application of nonreciprocal ferrite devices is questionable. The difficulties arise from absence of ferrite materials with the necessary properties. In the metric and decametric range of waves, the helicon devices may serve as a substitute for ferrite nonreciprocal devices. The main point is that the helicon devices use the gyroelectric effects in semiconductors instead of the gyromagnetic one in ferrites. A mathematical model describing the electrical properties of non-reciprocal quadripole has been presented. It has been shown that for the development of mobile non-reciprocal devices a semiconductor material of high carrier mobility $\mu > 4 \text{ m}^2\text{V}^{-1}\text{s}^{-1}$ and high carrier density $N > 10^{22} \text{ m}^{-3}$, ($T = 300\text{K}$), is needed. The electrical parameters of semiconductors should be stable in operational temperature range. The characteristics of the helicon isolators containing nonreciprocal transformer with helicon dimensional resonator are calculated. The experimental results are in compliance with calculations what confirms adequacy of used model.

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