

Experimental and theoretical study of the microwaves transmission through the plasma structures and layers in a constant magnetic field

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Abstract. The possibility of significant improvement transmission conditions of microwave radiation passing through a homogeneous quasi-neutral plasma layer in the constant magnetic field \mathbf{B}_0 is considered. The study based on 1D analysis was conducted for layers with concentration $N_p = 10^{17}\text{--}10^{19} \text{ m}^{-3}$ and collision frequency of electrons with molecules $\nu = 10^{10}\text{--}10^{11} \text{ s}^{-1}$ in the wavelength range $\lambda = 1\text{--}10 \text{ cm}$. For different values of plasma parameters N_p and ν the dependences of the magnetic induction values $B_0(\lambda, \alpha, |D|_{\text{cr}})$, reducing a transmitted wave amplitude attenuation to a specified level (in this case, $|D|_{\text{cr}} = 3 \text{ dB}$) were obtained. Analyzed the influence of the angle between vectors \mathbf{B}_0 and \mathbf{k} (wave vector) on the amplitude A_T and, hence, on the value of $B_0(\lambda, \alpha, |D|_{\text{cr}})$, revealed the optimal conditions of the field \mathbf{B}_0 orientation relative to the direction of electromagnetic waves propagation. Experimentally investigated the influence of a constant magnetic field B_0 on the attenuation degree of microwave radiation ($f = 13 \text{ GHz}$) in a various types plasma structures and in the plasma layers. The experiments were carried out in air at pressures $P = 70\text{--}500 \text{ Torr}$. A marked increase in the amplitude of the transmitted wave in presence of constant magnetic field was indicated.

The amplitude of electromagnetic (EM) wave passing through the dense plasma is significantly reduced. The well known possibility to diminish the amplitude attenuation is to use a constant magnetic field which strongly effects on the plasma properties [1].

In this work we present modeling results of microwave coupling to the dense magnetoactive plasma with parameters

$$N_p = 10^{19} \text{ m}^{-3}, \quad \nu = 10^{10}\text{--}10^{11} \text{ s}^{-1}, \quad (1)$$

where N_p is the plasma density, ν is the transport frequency of electron collisions with heavy particles. Here we have also experimentally demonstrated the possibility of using a constant magnetic field B_0 to improve the conditions of microwave radiation transmission ($\lambda = 2.3 \text{ cm}$) through a strongly inhomogeneous plasma formation.

A linearly polarized EM wave of amplitude A_0 and frequency $f = \omega/2\pi$ interacts with the quasi-neutral weakly ionized magnetoactive plasma. The study is carried out in the wavelength



range

$$\lambda = 1\text{--}10 \text{ cm.} \quad (2)$$

Under the condition (2) over the period of the electric field oscillation $T = 2\pi/\omega$ the ions are immobile. In addition, we neglect thermal motion of electrons.

The first step in the investigation is to consider the problem in the framework of 1D model. Such simplest approach is justified when the transverse dimensions of the plasma region considerably exceeds the wavelength. 1D analysis allows (i) for different plane plasma layer parameters to estimate the magnetic induction value, which is necessary to increase the amplitude of transmitted EM wave to the desired level, (ii) to identify the effect of magnetic field orientation relative to the wave vector and electric field vector of incident radiation.

EM wave $\text{Re} [\mathbf{E}_0 \exp(i(\omega t - k z))]$ with electric field components $E_{0,\mu}$ ($\mu = x, y$) propagates in the z direction. The wave vector $k = \omega/c$ is oriented perpendicular to the plasma layer which is localized on the interval $[0, \Delta]$:

$$N_p(z) = \begin{cases} N_p, & \text{if } 0 \leq z \leq \Delta, \\ 0, & \text{if } z < 0, z > \Delta. \end{cases} \quad (3)$$

The vector \mathbf{B}_0 is in the yz plane.

The solution of Maxwell curl equations for the complex amplitude of the electric field can be written in the form

$$\mathbf{E} = \text{Re} \left[\exp(i\omega t) \begin{cases} \mathbf{E}_0 \exp(-ikz) + \mathbf{E}_R \exp(ikz), & \text{if } z \leq 0 \\ \sum_{j=1}^2 \left(\mathbf{E}_j^{(+)} \exp(-ik\gamma_j z) + \mathbf{E}_j^{(-)} \exp(ik\gamma_j z) \right), & \text{if } 0 < z \leq \Delta \\ \mathbf{E}_T \exp(-ikz), & \text{if } z \geq \Delta \end{cases} \right], \quad (4)$$

where and \mathbf{E}_R and \mathbf{E}_T are the complex amplitudes of the reflected and the transmitted waves respectively,

$$\gamma_{1,2}^2 = 1 - \frac{N_* (1 - i\nu_* - N_*)}{(1 - i\nu_*) (1 - i\nu_* - N_*) - \left(\frac{\Omega_* \sin \alpha}{\sqrt{2}} \right)^2 \pm \sqrt{\left(\frac{\Omega_* \sin \alpha}{\sqrt{2}} \right)^4 + (\Omega_* (1 - i\nu_* - N_*) \cos \alpha)^2}},$$

where $N_* = \omega_{Le}^2/\omega^2 \equiv N_p/N_{cr}$, $\omega_{Le}^2 = e^2 N_p/(m\epsilon_0)$, $N_{cr} = \omega^2 m\epsilon_0/e^2$, $\nu_* = \nu/\omega$, $\Omega_* = \Omega/\omega$, $\Omega = |e|B_0/m$, ϵ_0 is the permittivity of free space, m is the electron mass, e is the electron charge, α is the angle between the vectors \mathbf{B}_0 and \mathbf{k} ($\mathbf{k} = k\mathbf{n}_z$, \mathbf{n}_z is the unit vector in the z direction). It should be noted that within the layer of the magnetoactive plasma (i) two waves propagate in the $(\pm) z$ direction

$$\text{Re} \left[\mathbf{E}_{1,2}^{(\pm)} \exp(i(\omega t \mp k\gamma_{1,2} z)) \right], \quad (5)$$

(ii) the components of the complex amplitudes E_μ are related by

$$E_{j,x} = h_j E_{j,y}, \quad (6)$$

where $h_{1,2} = i \left(q \pm \sqrt{q^2 + 1} \right)$, $q = \Omega_* \sin^2 \alpha / (2(1 - i\nu_*) \cos \alpha)$.

Using the boundary conditions

$$E_\mu(z = -0; -\Delta) = E_\mu(z = +0; +\Delta), \quad \frac{dE_\mu}{dz}(z = -0; -\Delta) = \frac{dE_\mu}{dz}(z = +0; +\Delta), \quad (7)$$

we obtain the expressions for the complex amplitudes \mathbf{E}_R , $\mathbf{E}_j^{(\pm)}$, \mathbf{E}_T .

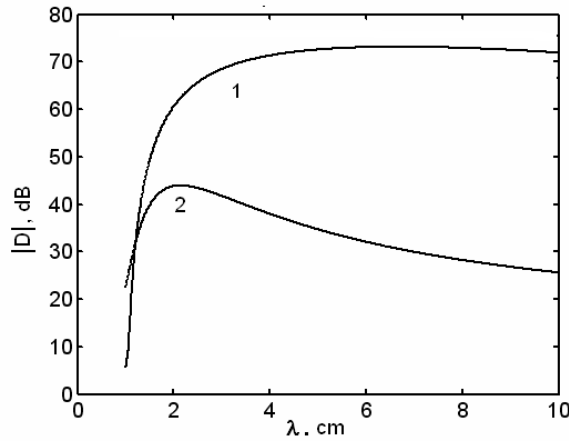


Figure 1. The dependencies of the attenuation value $|D|$ of the electric field amplitude on the wavelength in nonmagnetized plasma under conditions: $N_p = 10^{19} \text{ m}^{-3}$, curve 1— $\nu = 10^{10} \text{ s}^{-1}$, curve 2— $\nu = 10^{11} \text{ s}^{-1}$, $\Delta = 3 \text{ cm}$.

The level of radio transparency of the plasma layer is conveniently described by using the values

$$D = 10 \lg \frac{A_T}{A_0} < 0, \quad (8)$$

measured in decibels. Here A_T is the amplitude of transmitted wave

$$A_T = \sqrt{|E_{T,x}|^2 + |E_{T,y}|^2}, \quad (9)$$

where

$$E_{T,(x,y)} = \frac{4E_W}{h_2 - h_1} \sum_{j=1}^2 \left(\frac{1}{h_j} \right) \frac{F_j \gamma_j \exp(-i(\gamma_j - 1)\Delta_*)}{(\gamma_j + 1)^2 - (\gamma_j - 1)^2 \exp(-2i\gamma_j \Delta_*)},$$

$\Delta_* = k\Delta$, $F_1 = h_2 \cos \vartheta - \sin \vartheta$, $F_2 = h_1 \cos \vartheta - \sin \vartheta$.

Let us analyze the expression (9) for the cases $\Delta = 3 \text{ cm}$, $N_p = 10^{19} \text{ m}^{-3}$, $\nu = 10^{10} \text{ s}^{-1}$ and 10^{11} s^{-1} .

Figure 1 shows the dependencies $|D(\lambda)|$ in the case when $B_0 = 0$. With the increase in the frequency of electrons collisions ν the electrical conductivity $\sigma = e^2 N_p / m\nu$ decreases. Hence, the plasma becomes more transparent to microwaves—the value $|D|$ drops practically all over the range of wavelengths.

In a constant magnetic field the plasma layer becomes more transparent. With given attenuation level $|D|$ (we used a value of $|D|_{\text{cr}} = 3\text{dB}$) for each wavelength the value of the magnetic induction B_0 corresponding to this level can be found. Figure 2 shows the dependencies of the magnetic induction on the wavelength for the case of $\alpha = 0$ ($\mathbf{B}_0 \parallel \mathbf{k}$). Curve 1 (rare collisions $\nu \ll \omega$) has breaks at points $\lambda \approx 3.1$ and 5.1 cm associated with non-monotonic behavior of the function $|D(B_0)|$ near the values $|D|_{\text{cr}}$ in the small neighborhoods of these points. In the limit of frequent collisions $\nu \gg \omega$ (curve 2) the value $B_0(\lambda, \alpha, |D|_{\text{cr}})$ increases about twice in all wavelength range. Note that in this case the value $|D|$ drops to the level $\approx |D|_{\text{cr}}$ when Hall's parameter $\beta = \Omega/\nu$, is about 5.6.

Figure 3 demonstrates the influence of the angle α between the vectors \mathbf{B}_0 and \mathbf{k} on a value $B_0(\lambda, \alpha, |D|_{\text{cr}})$ in the layer $N_p = 10^{19} \text{ m}^{-3}$, $\nu = 10^{11} \text{ s}^{-1}$. As follows from the figure that (i) when the vectors \mathbf{B}_0 and \mathbf{k} have the same sense of direction the value $B_0(\lambda, \alpha, |D|_{\text{cr}})$ is at its minimum, (ii) under the condition $\alpha \leq 0.1\pi$ the angle dependence $B_0(\lambda, \alpha, |D|_{\text{cr}})$ is weak in the wavelength range $\lambda = 2\text{--}10 \text{ cm}$. This result remains correct in the case of rare collisions $\nu = 10^{10} \text{ s}^{-1}$.

The experiments were performed on microwave installation, the description of which is presented in [2]. The required configuration of the magnetic field created by ring-shaped magnet

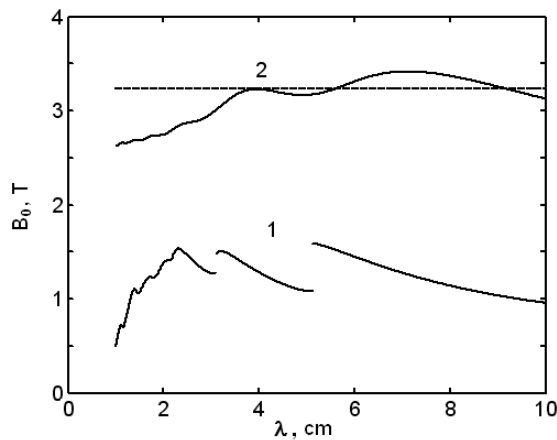


Figure 2. Magnetic induction $B_0(\lambda, \alpha, |D|_{\text{cr}})$, reducing the amount $|D(\lambda)|$ (see figure 1) up to level $|D|_{\text{cr}} = 3$ dB: (---)—line $\Omega = 5.6\nu$, $\alpha = 0$.

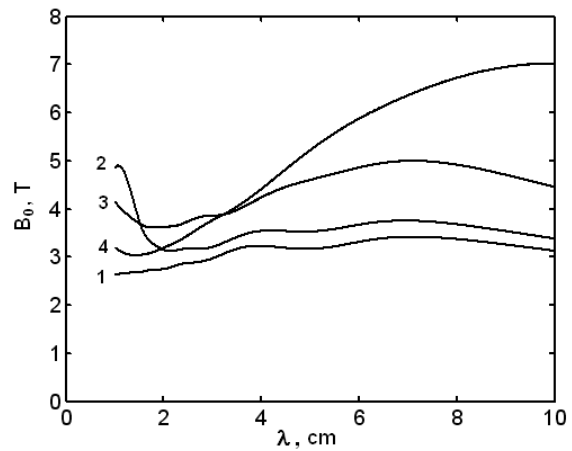


Figure 3. The dependences $B_0(\lambda, \alpha, |D|_{\text{cr}})$ in case $N_p = 10^{19} \text{ m}^{-3}$, $\nu = 10^{11} \text{ s}^{-1}$, $\Delta = 3 \text{ cm}$ when the values of the angle α between vectors \mathbf{B}_0 and \mathbf{k} $\alpha = 0$ (curve 1), 0.1π (curve 2), 0.2π (curve 3), 0.3π (curve 4). The angle θ between vector \mathbf{E}_0 and axis x $\theta = 0$.

($90 \times 60 \times 5 \text{ mm}^3$), hole size of which practically does not disturb the distribution of the microwave field in the focal region. EM wave ($\lambda = 2.3 \text{ cm}$) with amplitude $E \sim 3 \text{ kV/cm}$ freely transmitted along the magnet axis ($B_0 \approx 0.2 \text{ T}$) and fixed by antenna (open end cable) mounted on 20 mm from the its plane. The initiator of microwave discharge was set in the focus. The vacuum chamber was evacuated to 75 Torr and the microwave discharge of dipole type was produced at these conditions.

The main condition of the experiment was the need to create a bounded plasma structure in the form of one to three plasmoids. In this case the transmitted signal fixed rather stable. Bit more developed structure in the form of a chain of plasmoids greatly weakened the working signal. In the process of the experiment were also recorded parameters of the microwave setup and the signal from the photomultiplier (discharge glow). The results of the experiments in the form of oscillograms presented below in figure 4. The first and third beam display current and voltage of the magnetron. On the second channel (cyan) registered the signal from the microwave sensor, and the fourth (green)—signal from PMT.

It is clearly seen that the transmitted signal 2 in figure 4 (left-hand side) decreased to zero level without magnet in the presence of the discharge. The magnet placement (see figure 4, right-hand side) at focal region increases the level of the transmitting signal about twice. This effect has been checked and confirmed by us in various plasma structures generated by microwave discharge. However, experiments have shown that the level of the magnetic field of this magnetic ring allow register the effect only in a limited number of plasma structures. The transition to stronger magnetic fields, obviously, will allow us to research various options for the interaction of MW waves with complex discharge structures and layers and to identify the optimal conditions of it passing through the plasma. The experiments also showed a very interesting transformation of the bit structures in magnetic fields.

Thus, the influence of constant magnetic field on the attenuation of EM waves ($\lambda = 1\text{--}10 \text{ cm}$) in the layer of dense plasma with parameters $N_p = 10^{19} \text{ m}^{-3}$, $\nu = 10^{10}\text{--}10^{11} \text{ s}^{-1}$ theoretically has been studied. Unfortunately, the experimental capabilities do not yet allow full covering of calculated variants. And let us briefly denote the results of this work:

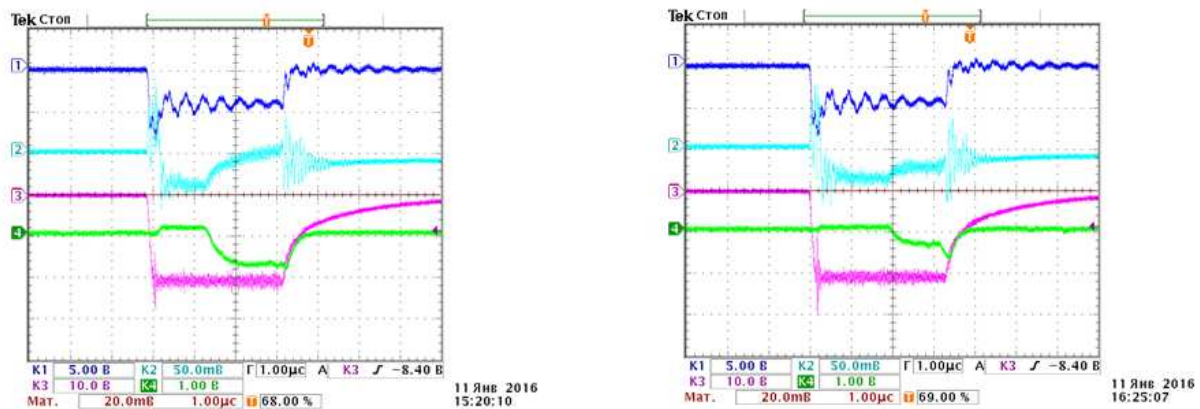


Figure 4. Signals waveforms: (from the left) discharge without magnet, (from the right) the same with magnet. On the second channel (cyan), registered is the signal from the microwave sensor, and the fourth (green)—signal from PMT.

- (i) When the vectors \mathbf{B}_0 and \mathbf{k} have the same sense of direction the value $B_0(\lambda, \alpha, |D|_{cr})$ is at its minimum B_{0min} .
- (ii) Under the condition $\alpha \leq 0.1\pi$ the angle dependence $B_0(\lambda, \alpha, |D|_{cr})$ is weak and $B_0(\lambda, \alpha, |D|_{cr}) \approx B_{0min}$ in the wavelength range $\lambda = 2-10$ cm.
- (iii) At parallel orientation of the vectors \mathbf{k} and \mathbf{B}_0 to reduce the value of the attenuation characteristic $|D(\lambda)|$ up to the level of 3 dB in the plasma layer with parameters $N_p \leq 10^{19} \text{ m}^{-3}$, $\nu \leq 10^{11} \text{ s}^{-1}$, $\Delta \leq 3$ cm, it is required to apply the magnetic field $B_0 \leq 3$ T.
- (iv) The possibility of using a constant magnetic field \mathbf{B}_0 to improve the conditions of microwave radiation ($\lambda = 2.3$ cm) transmission through a strongly inhomogeneous plasma formation is experimentally demonstrated.

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