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Resonant tunneling of electromagnetic signals in the presence of static magnetic field for mitigation of radiocommunication blackout

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The effect of the resonant tunneling of signals through an overcritical plasma layer in the presence of an external static magnetic field is considered. The aim of the study is to demonstrate the effectiveness of the combined usage of two methods for overcoming radio blackout for aircrafts moving in dense layers of the atmosphere at supersonic velocities: the method of resonant tunneling of the signal in the presence of a dielectric layer and the magnetic windows method. The features of dielectric resonator filling with an electromagnetic wave field are studied for various parameters. The values of the magnetic field induction providing the best signal propagation results through the plasma layer are estimated.

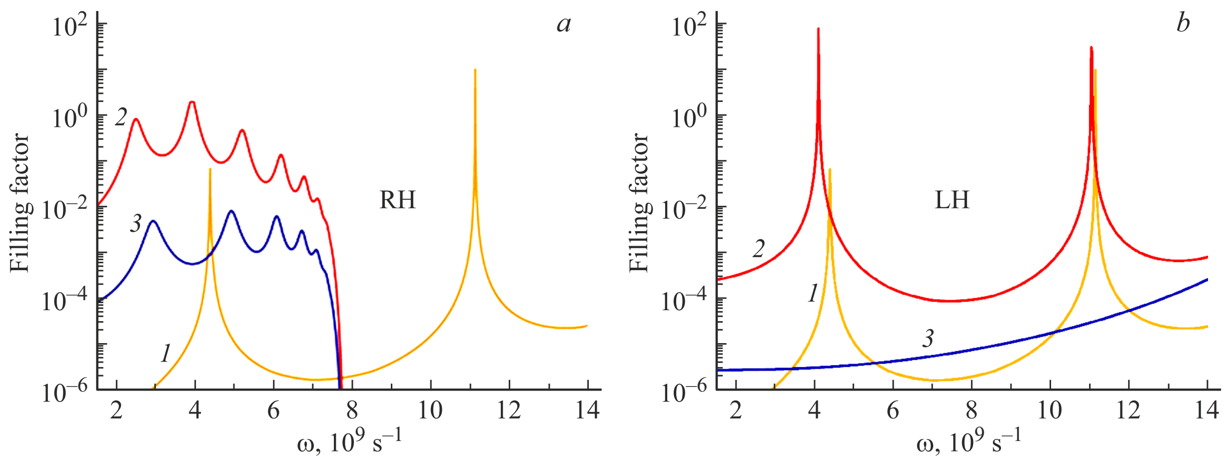
Keywords: Resonant tunneling, magnetic windows, radio blackout, air plasma.

1. Introduction

Aircrafts moving at high velocities (5 M and higher depending on the aircraft configuration [1]) in atmosphere are covered with plasma preventing radio communications, remote metering and GPS signal receipt for navigation [2]. This plasma sheath is formed due to the fact that the shock wave surrounding such aircraft causes heating and compression of the ambient air. As a result, air molecules are dissociated and ionized producing the plasma sheath. This plasma sheath usually has supercritical electron concentration, which sharply reduces the performance of the telecommunications channel between the aircraft and ground control due to signal reflection and absorption. Considerable efforts were made by various teams of researchers [3–5] (including operation at higher frequencies [4], aerodynamic shaping [1], electrophilic injection [5]) for suppression or mitigation of these negative impacts, however, they brought other problems. Finally, in the 1960s, a promising method was offered which was called „magnetic windows" [6] and is still extensively studied now [7,8]. The benefit of this method is that it does not affect the aerodynamic or thermal protection configuration of the aircraft. The method implies placement of a magnet under a transmitting-receiving antenna without influencing the antenna radiation. The principle behind such approach implies that the presence of static magnetic field $\mathbf{H}_0$ alters the electrons' motion in the plane transverse to $\mathbf{H}_0$. The important feature is that for right-handed waves there is a passband for frequencies not exceeding the cyclotron frequency ($\omega_c = \frac{eH_0}{cm}$), which does not depend on the plasma frequency and is defined only by the strength of the applied static magnetic field. And the strength of applied magnetic fields shall be about hundreds of oersted. Another promising method aimed at suppression of RF blackout is based on the concept of resonance tunneling of electromagnetic waves [9] through the supercritical plasma sheath [10–12]. Such tunneling becomes possible when the antenna localization area is coated with a dielectric layer which can be considered as an electromagnetic resonator. In such case, the signal will actively penetrate the opaque plasma sheath if its frequency coincides with the resonator eigenfrequency [10–12], which is defined by the dielectric coating parameters - width and permittivity. The benefit of this method is high resonance frequencies stability despite the rapidly changing during the flight plasma sheath parameters. Thus, search for efficient methods of RF frequency wave transport to the aircraft antenna and back is still an essential and not entirely solved problem. The study investigates whether two RF blocking avoidance methods may be combined — resonant tunneling in the presence of a dielectric resonator and provision of magnetic windows in the aircraft plasma sheath.

2. Numerical simulation

Consider the task of resonant tunneling of gigahertz waves through the „dielectric−plasma sheath" structure in the presence of external static magnetic field applied along the wave propagation direction. we will consider the normal incidence of the linearly polarized monochromatic wave on the „dielectric−conducting layer" structure with permittivity



Factor of dielectric filling with (a) right-handed (RH) wave field E^- and (b) left-hand polarized wave field E^+ in the presence of only dialectic layer (*1*), in the presence of only magnetic field (*3*) and in the presence of dielectric layer and external magnetic field (*2*) with induction $H_0 = 450$ Oe ($\omega_c = 8 \cdot 10^9\,\mathrm{s}^{-1}$), $\omega_p = 1.8 \cdot 10^{10}\,\mathrm{s}^{-1}$.

$\varepsilon_\omega(z)$. We will assume a weakly ionized air plasma layer as a conducting layer. Spatial distribution of electric field strength $E(z)$ of monochromatic wave with frequency ω is described by Helmholtz equation:

$$\frac{d^2E^\pm(z)}{dz^2} + \frac{\omega^2}{c^2}\varepsilon_\omega^\pm(z)E^\pm(z) = 0. \quad (1)$$

Here we have taken into account that for static magnetic field applied along the z axis, it is suitable to present a linearly polarized wave as a superposition of two circular waves $E^+ = E_x + iE_y$ (left-handed wave) and $E^- = E_x - iE_y$ (right-polarized). In this case, the permittivity for each of the waves will have the following view [13]:

$$\varepsilon_\omega^\pm = \begin{cases} \varepsilon_d & \text{in dielectric layer} \\ \varepsilon_{air} - \frac{\omega_p^2}{(\omega\pm\omega_c)^2+\nu^2}\frac{\omega\pm\omega_c}{\omega} + i\frac{\omega_p^2}{(\omega\pm\omega_c)^2+\nu^2}\frac{\nu}{\omega} & \\ & \text{in plasma layer,} \\ \varepsilon_{air} & \\ & \text{beyond the structure.} \end{cases} \quad (2)$$

Here, $\varepsilon_\omega^\pm$ is the permittivity for circular waves with various polarization rotation direction: $\mathbf{e}^\pm = \mathbf{e}_x \pm i\mathbf{e}_y$, $\mathbf{e}_x$ and $\mathbf{e}_y$ are unit vectors directed along the x and y axes, respectively; ε_d is the dielectric layer permittivity, $\omega_p^2 = 4\pi e^2 n_e/m$ is the plasma frequency, n_e is the electron concentration in plasma, m is the electron mass, ν is the transport collision frequency, $\varepsilon_{air} \approx 1$ is the air permittivity, $\omega_c = \frac{eH_0}{mc}$ is the cyclotron frequency.

We consider the structure with the following parameters: plasma layer with thickness $b = 10$ cm, electron concentration $n_e = 10^{11}\,\mathrm{cm}^{-3}$ ($\omega_p = 1.8 \cdot 10^{10}\,\mathrm{s}^{-1}$) and transport frequency $\nu \sim 10^8\,\mathrm{s}^{-1}$ [10]. In this case, the skin depth may be assessed as $\delta \approx c/\omega_p \approx 1.7$ cm. As a resonator, the dielectric layer $\varepsilon_d = 150$ [14] with thickness $a = 1$ cm is used. As said in [10], when incident radiation frequency coincides with the frequency of one of the resonator eigenmodes, effective wave „tunneling" through the plasma layer is observed and which results in resonator filling with the field providing successful signal detection. Resonant frequency position, in this case, is defined with good accuracy as follows:

$$\omega_n \approx \frac{\pi c}{a\sqrt{\varepsilon_d}}n, \quad (3)$$

where a is the dielectric layer thickness, n is the resonance number ($n = 1, 2, 3, \ldots$).

The Figure shows resonator filling factors F with the electric wave field without magnetic field and with static magnetic field, which as in [10] constitute a ratio of squared absolute maximum value of field strength of the wave filling the resonator to the incident wave. It should be noted that we use $\omega_p \gg \omega$, $\omega_c \gg \nu$. The Figure shows that the presence of the magnetic field qualitatively changes the type of dielectric resonator filling with a wave field. Expression (2) shows that, without magnetic field $\mathrm{Re}(\varepsilon_\omega) < 0$ in plasma layer, therefore, the plasma constitutes a reflecting barrier for frequencies $\omega < \omega_p$, except for the selected set of frequencies, for which resonance condition (3) is met. In the presence of magnetic field, for signal frequencies $\omega < \omega_c$ the sign of the real part of permittivity is changed for E^- (RH) waves Thus, for this frequency domain, plasma is no longer a reflecting medium, but rather forms a resonator that ensures efficient signal penetration through the plasma layer (curve *2* in Figure a). For E^+ (LH) wave the presence of magnetic field weakens the barrier properties of the plasma and , thus, increases the resonator filling factor at the resonator frequencies (curve *2* in Figure b) [10].

It is shown that filling factor F varies regularly with increasing ω for E^- waves. The minima are due to coherent reflections from the plasma sheath edges. Peaks, on the contrary, are observed when the reflected waves are put together out of phase and , thus, entire radiation goes into the resonator. It should be noted that peaks in our diagram are nonequidistant because plasma refraction index $n_\omega = \sqrt{\varepsilon_\omega}$ defining the peak positions by frequency is different for incident waves with different frequencies. It should also be noted that it is a combined effect of the presence of resonator and static magnetic field that ensures the best wave tunneling effect into the resonator area (see curves *3* without resonator in the Figure, *a, b*).

Conclusion

The study investigates the features of resonant signal propagation in resonant „dielectric–conductor" structure in the presence of external static magnetic field. For right-polarized wave (E^-), a rather wide (spectral range of about ω_c) spectral zone of effective wave tunneling through the plasma layer was formed provided that 450 Oe magnetic field was applied to the structure. For left-polarized (E^+) wave, such field increases the resonator filling factor by 3 orders of magnitude for the resonant frequency. It has been found that combination of „magnetic windows" and resonant „dielectric–conductor" structure increases the fraction of the signal penetration through the plasma layer by an order of magnitude.

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Conflict of interest

The authors declare that they have no conflict of interest.

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