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Resonant interaction of electromagnetic wave with plasma layer and overcoming the radiocommunication blackout problem

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Abstract

We present an analysis of the possibility of penetrating electromagnetic waves through opaque media using an optical-mechanical analogy. As an example, we consider the plasma sheath surrounding the vehicle as a potential barrier and analyze the overcoming of radiocommunication blackout problem. The idea is to embed a «resonator» between the surface on the vehicle and plasma sheath which is supposed to provide an effective tunneling of the signal to the receiving antenna. We discuss the peculiarities of optical mechanical analogy applicability and analyze the radio frequency wave tunneling regime in detail. The cases of normal and oblique incidence of radiofrequency waves on the vehicle surface are studied.

Keywords: blackout problem, electromagnetic wave tunneling, optical-mechanical analogy, waves in plasma

(Some figures may appear in colour only in the online journal)

1. Introduction

Analysis of the tunneling processes for electromagnetic waves in opaque media regions on the basis of the well-known optical-mechanical analogy is used in various perspective areas [1]. Typically, these are problems in condensed matter physics, magnetic hydrodynamics, quantum optics, physics of photonic crystals and artificial metamaterials with unique parameters [2–7].

We propose to use this technique for analyzing of the electromagnetic field interaction with low-temperature plasma layers in order to search for new physical ideas that are useful for different applications. Here we exploit mathematical identity of the stationary Schrödinger equation in quantum mechanics for the particle motion in potential field and Helmholtz equation in wave theory. The frontiers of applications allow us to formulate new unobvious limitations on the region of applicability of optical-mechanical analogy in problems of the transfer of electromagnetic waves through layers/structures of extremely low transparency. In particular, this problem is actually for ensuring constant contact with supersonic aircraft [8–16].

When choosing the parameters of plasma and electromagnetic radiation, we proceeded from the fact that aircrafts and rockets moving at supersonic speed in the atmosphere are covered with plasma sheath with thickness, \( d \), of about 0.1–1 m. Hence, we cannot use for telemetry and control microwaves with frequencies less than the so-called plasma frequency (of about 9 GHz for the object velocities in the range of 8–15 Mach) and wavelengths comparable or less than...
d. We cannot ignore the presence of a plasma sheath since it is the frequency range from 100 MHz to 10 GHz that is most important for prospective telecommunication systems [17–21]. Plasma destruction (e.g. by injecting water drops) is also quite a difficult task. It is also possible to reduce the plasma density near the vehicle by applying additional external electric or magnetic fields which is proposed in [22, 23]. However, the strength of the fields to be applied is large and realization of the idea is rather complicated.

Interesting possibilities are discovered when using the features of the interaction of an ionized gas with radiation. For overcoming the opaque layer one can use the nonlinear interaction of three waves in the plasma layer region: a low-frequency wave carrying a signal from the Earth, a Langmuir wave and a high-frequency wave (pump wave) generated from the onboard source. The reflected (so-called Stokes wave) carries the information encoded in the signal to the Earth [17, 18]. Significant progress can be achieved if we introduce an additional layer of double-positive (DPS) material covering the antenna and providing matching with the plasma sheath [21].

In this work we suggest the use of optical-mechanical analogy [1] to determine the conditions for the most effective transmission of signal through a plasma layer. This analogy allows us to introduce the concept of tunneling of electromagnetic waves by analogy with the resonant tunneling of a particle through potential barriers in heterostructures [24–27] and electron transport in quantum cascade lasers [28]. In the considered problem plasma sheath may act as such a ‘barrier’.

2. Method: the concept of optical mechanical analogy

Let us consider spatially inhomogeneous nonmagnetic medium characterized by the susceptibility \( \chi \), or permittivity \( \varepsilon \). In the case of monochromatic field \( \vec{E}, \vec{H} = \vec{E}_0(\vec{r}), \vec{H}_0(\vec{r})e^{-i\omega t} \), \( \omega \) is the frequency) Maxwell equations for electric and magnetic field strength can be written as:

\[
\begin{align*}
\vec{\text{rot}} \vec{E} &= \frac{i}{\varepsilon} \vec{\text{rot}} \vec{H}, \quad \text{div} \left( \varepsilon \vec{E} \right) = 0, \\
\vec{\text{rot}} \vec{H} &= -\frac{i}{\varepsilon} \vec{\text{rot}} \vec{E}, \quad \text{div} \vec{H} = 0.
\end{align*}
\]

From (1) one can obtain the following equation for electric field strength \( \vec{E} \):

\[
\Delta \vec{E} + \nabla \left( \frac{1}{\varepsilon} (\vec{E} \nabla) \varepsilon \right) + \frac{\varepsilon \omega^2}{c^2} \vec{E} = 0.
\]

For the case when permittivity depends only on one spatial coordinate \( \varepsilon = \varepsilon(z) \) and wave field propagates along this direction the equation (2) transforms to the well-known Helmholtz equation for the spatial distribution of electric field strength \( E \):

\[
\frac{d^2 E}{dz^2} + \kappa_0^2 (1 + 4\pi \chi(z)) E = 0
\]

with \( \kappa_0^2 = \omega^2/c^2 \). Here the electric field is perpendicular to \( z \)-axis.

Figure 1. The concept of overcoming of radio communication blackout: profile of the ‘potential barrier’ \( V(z) \leftrightarrow (1 - \varepsilon(z)) \) containing a vehicle surface (I), dielectric layer with embedded antenna (II) and plasma sheath (III). (IV) corresponds to the region of infinite motion of the electromagnetic wave (atmospheric air).

Equation (3) is mathematically equivalent to the stationary Schrödinger equation in quantum mechanics for the particle wave function \( \psi(z) \) in the potential field \( V(z) \):

\[
\frac{d^2 \psi}{dz^2} + \kappa_0^2 \left( 1 - \frac{V(z)}{\zeta} \right) \psi = 0,
\]

where \( \kappa_0^2 = 2m\zeta/h^2 \) is the wave vector of the particle with energy \( \zeta \). Direct comparison of equations (3) and (4) leads to the conclusion that potential function \( V(z) \) in quantum mechanics is similar to the susceptibility in electromagnetic theory \( (2m/h^2) V(z) \rightarrow (1 - \varepsilon) \cdot (\omega/e)^2 \).

Thus the eigenvalue problem for the Hamiltonian in quantum theory turns out to be mathematically identical to the problem of calculating the stationary distribution of the electric field strength in a wave. The medium with \( \varepsilon > 0 \) can be associated with an attractive potential \( V(z) < 0 \) (potential well) while the medium with \( \varepsilon < 0 \) acts as potential barrier \( V(z) > 0 \). In particular, the transport of the electron flux in heterostructures is mathematically identical to the problem propagation of electromagnetic waves through inhomogeneous media.

If the potential curve \( V(z) \) has the piecewise-continuous structure (figure 1), both the \( \psi \)-function and its derivative \( d\psi/dx \) should be continuous functions in the potential breaking points. Similar boundary conditions appear to exist in electromagnetic theory: the tangential components of \( \vec{E}, \vec{H} \) should also be continuous functions at the interface regions. Using Maxwell equations, one can rewrite the boundary conditions as the continuity of tangential components of \( \vec{E} \) and its derivative. For the normal incidence when only tangential components of \( \vec{E}, \vec{H} \) have the non-zero values these boundary conditions are equivalent to boundary conditions for the wave function in quantum mechanics.

The above conclusion, known as an optical-mechanical analogy in quantum theory, gives rise to a lot of practical applications and transfer the quantum theory problem solutions to optics and vice versa. As an example, the quantum
mechanical tunneling or the penetration of the quantum object through the barrier with a height greater than its kinetic energy is similar to the propagation of electromagnetic wave through the region with negative permittivity. It should be noted that plasma is an excellent example of the media with negative permittivity if the frequency of transmitted radiation is less than the plasma frequency. Actually, for the collisionless plasma the permittivity reads

\[ \varepsilon_p = 1 - \frac{\omega_p^2}{\omega^2}, \]

where \( \omega_p^2 = 4\pi e^2 n_e \text{ m}^{-1} \) is the plasma frequency squared and \( n_e \) is the electron density. From this point of view the plasma sheath appearing around the hypersonic vehicle during the flight looks like a potential barrier for the target transmission frequencies less than plasma frequency.

3. Main idea: the concept of overcoming of the radio communication blackout

In this section we are going to use the above mentioned optical mechanical analogy to propose the way of overcoming the communication blackout. We consider the ideal conductive surface of vehicle covered by the dielectric layer (thickness \( a \)) with permittivity \( \varepsilon_d \) and plasma sheath (thickness \( d \)) with permittivity \( \varepsilon_p \). Such a structure can be considered as an electromagnetic resonator, and from quantum-mechanical point of view it is similar to the potential well separated from the area of infinite motion by a potential barrier (see figure 1).

Let us imagine that quantum mechanical flux of particles in space is reflected from the barrier if the energy of incident radiation coincides with the position of one of the energy levels in the well the tunneling and filling will have resonant character. This will result in effective filling of the resonator (dielectric layer) the wave-field will penetrate through the plasma sheath and fill the resonator even in the case when \( \omega < \omega_p \). In the nonresonant case, the wave field is dominantly rejected from the plasma layer and filling is negligible.

3.1. Normal incidence

We will start our consideration of overcoming the radio communication blackout problem from the case of normal incidence of the electromagnetic wave on the hypersonic vehicle. Moving at hypersonic speed through the Earth’s atmosphere, it creates around itself a layer of air plasma of \( d \approx 5 - 10 \text{ cm} \) thickness with electron concentration about \( n_e \approx 10^{10} - 10^{11} \text{ cm}^{-3} \) [29]. For such values of concentration, one obtains \( \omega_p \approx 1 - 2 \times 10^{16} \text{ s}^{-1} \). If we take into account the collisions of electrons plasma permittivity becomes complex:

\[ \varepsilon_p = 1 - \frac{\omega_p^2}{\omega^2 + \nu^2} + i \frac{\omega_p^2 \nu}{(\omega^2 + \nu^2)\omega}. \]

Here \( \nu \) is the transport frequency. For the gas concentration \( N \approx 10^{16} - 10^{17} \text{ cm}^{-3} \) (we consider the atmospheric air at heights of several dozens of kilometers) and plasma temperatures of 1500–3000 K one obtains \( \nu \approx 10^8 - 10^9 \text{ s}^{-1} \) [10, 14–16]. The imaginary part of permittivity leads to absorption of the radiation in plasma. Similarly, the imaginary part of potential function \( V(z) \) in quantum theory provides the possibility to introduce the absorption or birth of the particles in the flux.

As it has been already noted to provide the effective tunneling of electromagnetic wave through the plasma barrier one should cover the surface of the vehicle by the dielectric layer \( \varepsilon_d \). Then this layer covered by the plasma sheath will act as an electromagnetic resonator, and we propose that the filling of it will have the resonant character. The receiving antenna should be located in the resonator (i.e. embedded into the dielectric layer in the region of antinode of a standing wave) and in the case of resonant tunneling its interaction with incoming signal should be rather effective.

For simplicity we assume that the plasma layer is characterized by rectangular profile of the electron density. If we suppose that the vehicle surface is ideally conductive then the following permittivity profile in our calculations can be written:

\[ \varepsilon(z) = \begin{cases} \varepsilon_d, & 0 \leq z \leq a \\ \varepsilon_p, & a < z \leq a + d \\ \varepsilon_{air}, & z > a + d \end{cases}. \]

Here \( a \) is the thickness of dielectric layer with permittivity \( \varepsilon_d \), \( \varepsilon_{air} = 1 \) is the permittivity of the atmospheric air. If \( |\varepsilon_d| \gg 1 \) the assumption that the height of the potential well is infinitely large is valid. Hence, spectrum of standing waves in dielectric layer is determined by \( k_n \approx (\pi / a) n \), \( n = 1, 2, 3 \ldots \), therefore resonant frequencies are

\[ \omega_n \approx \frac{\pi c}{a\sqrt{\varepsilon_d}} n. \]

For example, for dielectric layer with \( a = 1 \text{ cm} \) and \( \varepsilon_d = 150 \) (this corresponds to novel ferroelectric polymer composites [30]) we obtain \( \omega_1 \approx 7.7 \times 10^9 \text{ s}^{-1} \) (\( f \equiv \omega / 2\pi = 1.2 \text{ GHz} \)). In particular for \( n_e = 10^{11} \text{ cm}^{-3} \) (\( \omega_p \approx 1.8 \times 10^{10} \text{ s}^{-1} \)) and \( \nu = 10^{8} \text{ s}^{-1} \) one obtains two stationary states in resonator \( (n = 1, 2) \) for frequencies \( \omega_n < \omega_p \). It means that we have two values of the income radiation frequency that can effectively fill the resonator and interact with antenna.

The solutions of wave equation (3) with the piecewise permittivity profile (7) can be found analytically in each spatial region:
it means that the electric field strength has zero value at resonator. states within the framework of the optical-mechanical analogy. A vertical dashed line indicates the optimal location of the antenna in the amplitude of the incident wave field and of the reflected from the plasma layer field; where (10) incoming radiation flux:

\[ F = \frac{|E_d|^2}{|E_{a+}|^2} \]  (10)

where \( |E_d|^2 \) and \( |E_{a+}|^2 \) are the squared absolute values of electric field strength. On the other hand, the energy fluxes are proportional to the squared field strength amplitudes. Hence the introduced filling factor have the same sense as the attenuation factor commonly used.

The boundary conditions for electric field vector provide the set of equations for amplitudes in (9) which was solved numerically by the ‘Wolfram Mathematica’ package. As a result, filling factor \( F(f) \) in dependence on radiation frequency for given dielectric layer was obtained.

As can be seen from figure 2(a), the position and number of resonances essentially depends on thickness of dielectric layer: to shift the resonance to the lower frequencies one should increase the width of dielectric. There is the difference between resonant frequencies obtained by the equation (8) and in numerical calculations which are related to the finite height of the plasma barrier.

We would also like to note that the filling factor can be even greater than unity (see figure 2(a)). It means that the amplitude of the standing wave in the resonator can even exceed the amplitude of the wave in the incoming flux. Hence, the effect of resonant tunneling can even increase the signal to be detected by antenna. In some sense it means that proposed method can even amplify the signal.

For transferring critical data through a plasma sheath, the positions \( f_c \) and the widths \( \Delta f \) of the transparency peaks are of great importance. Figure 2(b) presents the resonant peaks behavior (the carrier frequency of the order of 1 … 2 GHz, the bandwidth of a few MHz) in dependence on dielectric properties. It is easy to see that tracking telemetry and command (TT&C) signals in the presence of plasma sheath are possible within the framework of our concept with reasonable parameters of the resonator used.

To analyze the attenuation of the signal due to the collisional absorption we present the simulations of the filling factor in dependence on transport frequency \( v \). First we mention that as in the given range of parameters the potential well is deep, i.e., \( |e_d| \gg 1 \), resonant frequencies do not depend on the value of \( v \). To estimate the role of absorption in the plasma layer due to collisional processes we perform the set of simulations of filling factor for the plasma permittivity given by expression (6) with \( n_e = 10^{11} \text{ cm}^{-3} \) and different values of transport frequency. These data are presented at figure 3(a) and demonstrate the rapid drop of the filling factor with the increase of transport frequency in the range \( \nu > 10^7 \text{ s}^{-1} \). It seems that this fact reduces the efficiency of the proposed method to fill the resonator. On the other hand, the increment of \( \nu \) leads to broadening of the resonant curve \( F(f) \) (see figure 3(b)) and
hence provides the possibility to employ wider spectrum of transmitted signal.

The dependence of filling factor on the electronic density in the plasma layer is displayed at figure 4. We see that with the increase of \( n_e \) the position of resonances slightly shifts towards higher values of frequency; the threshold value of this shifting is determined by the expression (8) that corresponds to the resonator with ideally conducted walls. Also one should mention the decrease of the filling factor value with increase of the electronic density both for resonant and nonresonant tunneling. This fact results from the decreasing of the tunnel transparency of the plasma layer for higher electronic densities.

To gain greater insight into the process of electromagnetic field penetration through the plasma sheath we present the data for spatial distribution of the absolute value of the electric field strength corresponding to two lower resonances (figure 5) and some frequency between them. The resonant distribution corresponds to the frequencies \( f_1 = 0.73 \) GHz (figure 5(a)), and \( f_2 = 1.87 \) GHz (figure 5(b)). Typical values of the penetration depth into the plasma can be estimated as \( \delta = 1/\kappa \approx 1/\sqrt{1 + \nu^2/\omega^2} \sim 1 \) cm (we suppose that \( \nu \ll \omega \)). This value is significantly less than the plasma sheath layer \( (\delta \ll d) \); as a result in a nonresonant case \( (f = 1.21 \) GHz) the penetration of electromagnetic signal through the plasma layer is not observed and the exponential attenuation in the layer is found to exist (see figure 5(a)).

Nevertheless for resonant frequencies \( (f_1 = 0.73 \) GHz, and \( f_2 = 1.87 \) GHz) the significant filling of the resonator takes place (see figures 5(b) and (c)). Moreover for \( f_2 = 1.87 \) GHz the filling factor is greater unity.

The performed calculations have been done using rectangular profile of the electron density in the plasma sheath. In reality, this profile is smoothed and depends on concrete hydrodynamic features of the plasma flow near the vehicle surface. At figure 6 there are the results for filling factor in

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**Figure 3.** The filling factor \( F \) in dependence on the transport frequency \( \nu \) for resonant frequencies \( f_1 = 0.73 \) GHz and \( f_2 = 1.87 \) GHz (a) and in dependence on \( f \) (1st resonance) (b). Calculations are performed for \( a = 1 \) cm, \( \varepsilon_d = 150, d = 10 \) cm, \( n_e = 10^{11} \) cm\(^{-3} \).

**Figure 4.** The filling factor \( F(f) \) in dependence on the transmitted signal frequency for different values of electronic density in the plasma layer, \( \nu = 10^8 \) s\(^{-1} \).

**Figure 5.** Spatial distribution of the absolute value of the electric field strength in nonresonant (a) and resonant (b) and (c) cases (the distribution is normalized to the incoming flux). Curves (b) and (c) correspond to the first and second eigen-frequencies of the resonator. Calculations are performed for \( a = 1 \) cm, \( \varepsilon_d = 150, d = 10 \) cm, \( n_e = 10^{11} \) cm\(^{-3} \), \( \nu = 10^8 \) s\(^{-1} \).
the case of Gaussian and super Gaussian electron density profiles (see equation (11), \( m = 2 \) and \( m = 4 \) correspondingly) obtained by direct numerical solution of the equation (3):

\[
n_e(z) = n_0 \exp \left( - \frac{(z - a)^m}{d^m} \right), \quad z \geq a. \tag{11}
\]

Parameters \( a \) and \( d \) and \( n_e \) correspond to those given earlier: \( a = 1 \) cm, \( d = 10 \) cm, \( n_0 = 10^{11} \) cm\(^{-3}\).

This solution was performed also in the Wolfram Mathematica package.

The comparison of simulations for rectangular and smoothed stationary profiles of the electron density demonstrates the qualitative similarity of them (see figures 2(a) and 6). The most important conclusion is that if the potential well is deep, the positions of the resonances do not depend on the electron density profile and is determined by resonator parameters.

To conclude the discussion we would like to note that dielectric layer with high value of permittivity should be covered by the heat-insulator sheet to prevent a contact with plasma and destruction. As an example of such protective layer we consider the sheet of silicon (permittivity \( \varepsilon_s \approx 10 \) with thickness of \( h = 1 \) cm). This additional sheet should obviously be taken into account when studying the resonance tunneling through the structure. In this case the resonator includes also the silicon sheet and becomes wider; so one can suppose that the resonant frequencies will shift to lower values. That is what we observe in our numerical simulations. The filling factor in the case of an additional silicon layer for the normal incidence is presented at figure 7. All the other parameters are similar to those used at figure 2 with \( a = 1 \) cm. The only essential difference is the shift of resonant frequencies that is clearly seen at the figure.

**3.2. Oblique incidence**

Here we are going to move up to the case of the oblique incidence of the electromagnetic wave on the above discussed structure. It is important to notice that in this case one can distinguish two types of electromagnetic waves: transverse electric (TE) and transverse magnetic (TM). Let us remind that in the TE wave vector \( \vec{E} \) is perpendicular to the plane of incidence while in TM wave \( \vec{E} \) belongs to it. Propagation of these two waves through the potential structure differs from each other. Schematically, these two cases of incidence are shown at figure 8.

Let us first consider the case of TE wave. Here we suppose that the wave vector lies in the \( xz \)-plane, \( \theta \) is the angle of incidence of electromagnetic wave counted off from the \( z \)-axis. In this case electric field has the only tangential \( x \)-component, while for magnetic field both \( y \) and \( z \) components are non-zero. Then the wave equation for electric field reads:

\[
\frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial z^2} + \varepsilon(z) \frac{\omega^2}{c^2} E = 0. \tag{12}
\]
This circumstance leads to the existence of resonance peaks. To demonstrate this fact, we present the filling factor for two values of dielectric layer permittivity, $\varepsilon_d = 10$ and $\varepsilon_d = 150$ (see figure 8). Actually, for $\varepsilon_d = 150$ which is within the range of particular interest for the problem of overcoming of the communication blackout the resonance shifting is negligible (figure 6(a)).

For the TM wave magnetic field has only the tangential $x$-component. Hence, it is handier to solve the wave equation for the magnetic field:

$$\frac{\partial^2 H}{\partial t^2} + \frac{\partial^2 H}{\partial z^2} + \varepsilon(z)\frac{\omega^2}{c^2}H = 0. \quad (15)$$

Provided that permittivity is piecewise continuous function in space equation (15) is identical to equation (12). Thus the solutions for magnetic field in each spatial region will be determined by expressions similar to (13). The difference appears when writing the condition for continuity of the tangential component of field $E$:

$$i\frac{\omega}{c}E_x = \frac{1}{\varepsilon} \frac{\partial H}{\partial z}. \quad (16)$$

It means that instead the continuity of $H$ and its derivative we have the continuity of $H$ and $\frac{1}{\varepsilon} \frac{\partial H}{\partial z}$. This circumstance leads to some peculiarities of the process of TM wave propagation through the plasma barrier: optical mechanical analogy will work only for TE wave propagation, TM wave propagation is beyond this analogy.

Physical reason for this is directly associated with the induced oscillations of the plasma barrier resulting from the existence of $z$-component of field $E$. We plan to study this aspect.
phenomenon in more detail in further publications. Actually, the phenomenon of electromagnetic wave tunneling is more complicated that the quantum-mechanical tunneling due to the vector nature of the electromagnetic field.

4. Conclusions

Thus, the new general approach is proposed to overcome the communication blackout during the hypersonic vehicle movement through the Earth’s atmosphere. The main idea is based on the optical-mechanical analogy which allows to consider plasma sheath surrounding the vehicle as a potential barrier and analyze the process of electromagnetic wave tunneling. It is demonstrated that dielectric layer covering the antenna surface can act as the resonator providing resonance tunneling at definite frequencies of the electromagnetic wave. It should be noted that the proposed technical solution can be of interest only for the case of TE wave. The resulting transparency windows allow the transfer of critical data.

In reality the electronic profile is nonstationary and depend on concrete hydrodynamical features of the plasma flow near the vehicle surface, that are typically varied in time. The problem of the operating frequency shift with the inevitable change in the parameters of the plasma barrier can be solved by using cognitive radio systems with tunable parameters [31]. The key to success in practice can become a combination of:

– modern approaches to exploit a radio environment with rapidly changing parameters;
– possibilities to control characteristics of the resonator by their changing, e.g. the effective dielectric permeability of ferroelectrics;
– possibilities to adjust the parameters of the barrier (plasma layer) with the help of relatively weak electric and magnetic fields.

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References

[1] Shvartsburg A B 2007 Phys.-Usp. 50 37