Anomalous linear absorption of an electromagnetic wave in an inhomogeneous isotopic plasma

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(Submitted October 4, 1976)
Pis'ma Zh. Eksp. Teor. Fiz. **24**, No. 10, 547–551 (20 November 1976)

We present experimental results that offer evidence that the maximum absorption coefficient of an electromagnetic wave incident on an inhomogeneous isotropic plasma can exceed the value 0.5 typical of only a linear layer. A qualitative interpretation of this phenomenon is given.

PACS numbers: 52.40.Db

In the absence of collisions, linear absorption of an electromagnetic wave of the TM type, incident on an inhomogeneous plasma layer, is determined by its transformation in the vicinity of the plasma resonance into damped plasma waves.[1] Calculations performed for layers that are smooth on the wavelength scale,[2,3] and also for a linear layer,[4] have given grounds for assuming 0.5 to be the maximum absorption coefficient for any concentration profile.

We present here results of an experimental investigation of plasma-layer absorption properties that prove that the layer can be so matched to an incident wave that the absorption coefficient may reach a value close to unity.

1. The plasma was produced by an induction high-frequency discharge in a hydrogen atmosphere at a pressure $(3-4)\times 10^{-4}$ Torr. The longitudinal distribution (in the direction of the inductor axis) of the concentration had a bell-shaped form with characteristic length $L/\lambda_0 \approx 3$ (Fig. 1). In the transverse direction, in the inductor plane, the distribution had an extended homogeneous section of diameter ~ 55 cm.

An electromagnetic wave from a 10-cm klystron oscillator with 10^{-3} W power was fed to the radiator through a waveguide channel that includes direc-

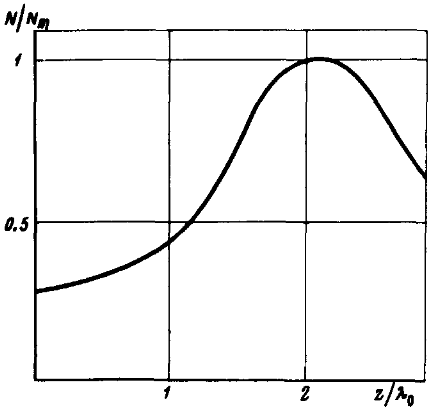

FIG. 1. Axial distribution of the concentration in the layer.

tional couplers, matching elements, and a vacuum seal. The relative error in the measurement of the reflected signal did not exceed 2%.

The radiator was the open end of a waveguide measuring 15×15 cm. The maximum transverse dimension of the region occupied by the field in the space between the radiator and the inductor did not exceed 30 cm, and the field at the plasma boundary decreased by 30 dB. Thus, the fact that the tranverse dimension of the plasma was bounded could not influence substantially the results of the measurements. To decrease the reflection from the chamber walls and to eliminate the enveloping of the plasma layer by the microwave signal, the chamber was lined on the inside with absorbing material.

The transmitted signal was registered with a receiving horn antenna . Qualitative investigations of the distribution of the field inside the chamber were carried out with the aid of a movable RF probe having a spatial resolution ~ 1 cm and insensitive to the polarization of the field. The determination of the maximum concentration in the layer was based on the transmitted signal with the concentration profile approximated by the expression for an Epstein layer of thickness $S = 2.5\lambda_0$. This method ensured an accuracy $\Delta N/N \approx 0.3$. More important for our present purposes, however, were measurements of the relative change of the concentration (from the change of the cutoff frequency), the accuracy of which reached 1—2%.

2. Figure 2 shows the dependence of the transmitted and reflected signals on the concentration of N_m of the electrons at the maximum of the layer. It is clearly seen that with increasing concentration the reflected signal, prior to levelling off to the value of incident signal ($|E_{\text{tr}}^2|/|E_{\text{inc}}^2| = 1$) goes through a minimum at $N_m/N_{\text{cr}} = 1.4$. A similar minimum was observed also on the frequency characteristic of the layer at a fixed value of N_m and at a frequency $\omega \approx 1.19\omega_m^{\text{cr}}$ (ω_m^{cr} is the critical frequency for the maximum concentration). The attenuation of the signal at the minimum reached 20 dB.

To explain the nature of this phenomenon, qualitative investigations were made of the distribution of the field in the plasma. They have shown that appearance of a reflected signal produces in the gap between the radiator and the inductor a standing wave whose amplitude first increases with increasing N_m, and then begins to decrease rapidly as N_m approaches the value $1.4N_{\text{cr}}$ (in agreement with the decrease of the reflected signal). At the same time, a maximum of the field appears in the region of the critical concentration (Fig. 3). Figure 2(b) shows the dependence of the amplitude of the standing wave on N_m/N_{cr}, calculated from the value of the signal at the probe. It is clearly seen that the obtained curve is similar in shape to the plot of $|E_{\text{tr}}|^2/|E_{\text{inc}}|^2$ against the concentration (Fig. 2a).

The experimentally observed increase of the field at the point where $\epsilon = 0$ is the well known effect of "swelling" in the region of the plasma resonance, wherein, in the absence of collisions ($\nu_{ei}/\omega, \nu_{em}/\omega \sim 10^{-4}$ in the experiment) the field can reach a value $E/E_0 \approx (r_{de}(\partial\epsilon/\partial z)|_{\epsilon=0})^{-2/3} \approx 10^2$ (E_0 is the field of the incident wave, r_{de} is the Debye radius, $(\partial\epsilon/\partial z)^{-1} \approx 10$ cm), and the characteristic dimension of the region occupied by the field is $\Delta z \approx [r_{de}^2/(\partial\epsilon/\partial z)]^{1/3} \approx 10^{-1}$ cm. Thus the signal from the probe is proportional to a certain value of the field averaged over its dimension, in our case it could increase by a factor V/V_0

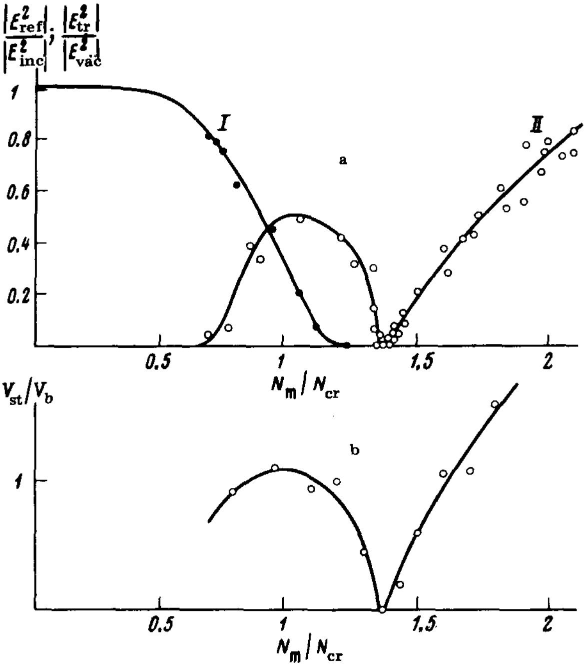

FIG. 2. (a) Dependence of the reflected (II) and transmitted (I) signals on the plasma concentration ($E^2_{\rm ref}$, $E^2_{\rm inc}$, $E^2_{\rm tr}$, and $E^2_{\rm vac}$ are respectively the signals reflected, incident, transmitted, and transmitted in the absence of a plasma). (b) Dependence of the standing-wave amplitude calculated from the probe signal and normalized to the signal in the absence of plasma, when the probe is located at the waveguide section V_b

$\approx (E/E_0)\Delta z/e \approx 10$. The experimentally observed maximum increase of the probe signal is $V/V_0=8.5$.

3. The obtained experimental data have necessitated a more critical approach to the analysis of the theoretical results on the absorption of waves with TM polarization by inhomogeneous layers. In particular, it turned out (for details see[5]) that the matched (nonreflecting) absorption can be realized in sufficiently sharp layers (with scales smaller than or of the order of the wavelength λ_0), for which $(\partial\epsilon/\partial z)|_{\epsilon=0}<0$ and $(\partial^2\epsilon/\partial z^2)|_{\epsilon=0}<0$, so that the models of a purely linear transition through $\epsilon=0$ are in this sense not optimal.[1-4] The corresponding approximate conditions can be easily understood from the following qualitative arguments. In the region where the TM wave does not propagate (i.e., beyond the turning point $z=z_t$, $\epsilon(z_t)=\chi^2=\sin\theta$, where θ is the angle of incidence of the wave on the layer), there are two characteristic sections, on which the plasma is equivalent to a certain lumped capacitance C (on the section $z_t<z<z_{|\epsilon=0}$) and lumped inductance L (on the section $z>z_{|\epsilon=0}$), and a narrow layer near $z_{|\epsilon=0}$ introduces a certain active resistance $R\approx 1/(\partial\epsilon'/\partial z)_{|\epsilon=0}$. The values of L and C can be estimated by averaging, which is essentially equivalent to piecewise-homogeneous approximation of the ϵ profile. For example, for layers of

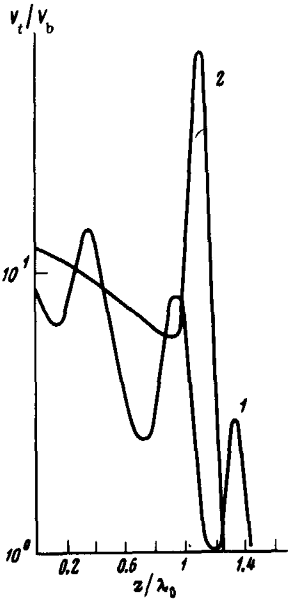

FIG. 3. Dependence of the probe signal in the presence of a plasma (V_t) normalized to the vacuum signal (V_b) on the position of the probe relative to the radiator: 1—$N_m/N_{cr} < 1.4$; 2—$N_m/N_{cr} = 1.4$.

the type $\epsilon = 1 - (z/l_0)^n$ (piecewise-homogeneous approximation) they take in the quasistatic case the form

$$\omega L \approx \sqrt{2}\,\frac{\sqrt{2\chi^2 - 1 - [2 - (1-\chi^2)^{1/n}]^n}}{[2 - (1-\chi^2)^{1/n}]^n - 1}; \quad \omega C \approx \frac{1}{2}\chi^2[1-(1-\chi^2)^{1/n}]^n k_o l_o;$$

$$R \approx \frac{1}{n}\pi\chi^2 k_o l_o .$$

In this notation, the matching conditions take the usual form: in the high-Q case ($R < \omega L$) resonance sets in at

$$\omega^2 LC \approx 1 \qquad (*)$$

and matching of the field incident on such a layer takes place at

$$L/RC \approx \sqrt{1-\chi^2} \qquad (**)$$

In particular, for a linear layer ($n = 1$) we obtain the well known resonance condition $\chi^2(k_0 l_0)^{2/3} = \text{const}$ and incompatibility of this condition with the condition (**), which in fact determines the limiting value of the transformation coefficient. Similar conditions of absorption without reflection can be obtained also for smooth layers.[5]

Of course, a real experiment takes place under more complicated conditions, but one can be sure that in the presence of sections with $(\partial\epsilon/\partial z)_{\epsilon=0} < 0$ and $(\partial^2\epsilon/\partial z^2)_{\epsilon=0} < 0$ at definite resonant frequencies there should occur an anomalous growth of the absorption (in comparison with the sections where $(\partial^2\epsilon/\partial z^2)_{\epsilon=0} = 0$).

The authors are most grateful to M. A. Miller, who called their attention to such a possibility of the interpretation of the experimental results, and to A. A. Zharov for useful discusssions.

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