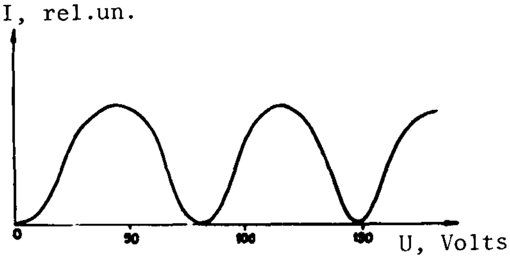

Intensity of light passing through $Ba_{0.25}Sr_{0.75}Nb_2O_6$ sample vs. amplitude of voltage applied to a sample of unit dimensions.

along [010] or [100] perpendicular to the broad face of the plate, and the electric field was applied along the c-axis.

The electrodes were made of aquadag, silver-filled paste, or silver evaporated in vacuum. The samples were made single-domain at temperatures 65 - 150°C (the Curie temperature is 60°C) in a field up to 10^4 V/cm applied along [001], followed by cooling in the field. The contact material exerted a noticeable influence on the half-wave voltage in the initial sample; it was necessary to choose a separate single-domain regime for each type of contact. An important role was played by the natural unipolarity, viz., when the voltage was applied in the unipolarity direction, the single-domain regime set in more rapidly and more effectively, without deterioration of the optical homogeneity of the samples. The degree with which the single-domain regime was reached was monitored against the minimum of the half-wave voltage at room temperature.

The light was modulated at frequencies from 0.1 to 2×10^4 Hz. The figure shows the variation of the intensity of the light passing through the sample against the amplitude of the voltage applied to a sample of unit dimensions. It should be noted that the domain structure in the $Ba_{0.25}Sr_{0.75}Nb_2O_6$ crystals becomes unstable even slightly above room temperature (35 - 45°C) [5], so that the samples become partly depolarized after becoming single-domain. This is the cause of the increased value ($\sim$ 70 V) of the half-wave voltage in weak fields. In the presence of a bias field exceeding $\sim$ 500 V/cm, the half-wave voltage is 50 V for a sample of unit dimensions, which is approximately 1/50-th the value for lithium-niobate crystals. The depth of modulation reaches under these conditions 98% at a beam aperture 4×4 mm. This demonstrates that barium-strongium niobate crystals are effective enough light modulators.

The authors thank N. A. Morozov for a discussion of the results.

[1] A. A. Ballman and H. Brown, J. Crystal Growth 1, 311 (1967).
[2] A. S. Sonin and A. S. Vasilevskaya, Elektroopticheskie krystally (Electro-optical Crystals), M., 1971.
[3] J. C. Brice, O. F. Hill, P.A.C. Whiffin, and J. A. Wilkinson, J. Crystal Growth 10, 133 (1971).
[4] O. F. Dudnik, V. B. Kravchenko, N. A. Morozov, and A. T. Sobolev, Fourth All-Union Conference on Crystal Growth, Papers on "Crystal Growth and Structure" (in Russian), part 2, p. 130, Erevan, 1972.
[5] Yu. L. Kopylov, V. B. Kravchenko, and O. F. Dudnik, in: P'ezo- i segnetomaterialy i ikh primenenie (Piezo- and Ferroelectric Materials and Their Use), M., 1972, p. 86.

PARAMAGNETIC EXCITATION OF ION-CYCLOTRON AND ION-ACOUSTIC WAVES IN A PLASMA WITH AN ALTERNATING ELECTRIC FIELD UNDER CONDITIONS OF THE LOWER HYBRID RESONANCE

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We present the results of experiments that have revealed paramagnetic excitation of ion-cyclotron and ion-acoustic oscillations of a plasma situated in an alternating electric field of frequency ω_0 close to the lower hybrid resonance frequency $\omega_{LH} = \omega_{pi}(1 + \omega_{pe}^2/\omega_{He}^2)^{-1/2}$

It is known that parametric excitation of various modes is possible in a plasma situated in an alternating electric field. Theoretical studies have shown that if the frequency of the pump field is close to the frequency of the lower hybrid resonance ω_{LH}, then ion-cyclotron and ion-acoustic oscillations are excited in the plasma [2 - 4]. Decay excitation of ion-acoustic oscillations are excited in the plasma [2 - 4]. Decay excitation of ion-acoustic oscillations was observed experimentally in [5] at a pump frequency $\omega_0 \gtrsim \omega_{LH}$. The study of these processes is of great interest when it comes to explaining the mechanism whereby a plasma is heated by an electromagnetic wave of frequency $\omega \sim \omega_{LH}$.

In our experiments, the electric field of the pump wave was excited by a discharge with oscillating electrons resulting from the development of two-stream instability of a plasma situated in constant longitudinal magnetic and radial electric fields. The setup and the topography of the constant fields are described in [6]. The magnetic field intensity varied in the range H = 200 - 800 Oe, the anode voltage was U = 1 - 2 kV, and the pressure of the working gas (air) was $P = (0.5 - 2)\times 10^{-4}$ mm Hg. The operating regime was stationary.

An azimuthal electron stream with felocity $v_\phi = cE_2/H \gg v_{Ti}$ (v_{Ti} is the thermal velocity of the ions) is produced in the employed discharge. It becomes possible in this case to excite high-frequency oscillations with frequency $\omega = k_\phi v_\phi$ and growth rate $\gamma \gg \omega_{Hi}$, where $k_\phi = m/r$ is the azimuthal wave number [7]. The experimentally observed oscillations have m = 1, and their frequency is $2\pi f_0 = \omega_0 \simeq k_\phi v_\phi$. The angle θ ($\cos\theta = k_\parallel/k_\perp$, where $k_\parallel$ and $k_\perp$ are the components of the wave number) was close to $\pi/2$. The azimuthal component of the wave field at the maximum was $\tilde{E}_\phi \lesssim 5$ V/cm. As seen from Fig. 1, the frequency $2\pi f_0$ as a function of the magnetic field intensity H could be close to $\omega_{LH} \simeq \omega_{pi} \simeq 5\times 10^{-7}$ sec^{-1} (the plasma density on the axis is $n_0 = (8 - 9)\times 10^9$ cm^{-3}, $\omega_{pe}^2 \ll \omega_{He}^2$. It is just under these conditions that parametric excitation of low-frequency plasma oscillations were observed.

A frequency f_1 ($2\pi f_1 = \omega_{pi}$), lower by an amount $\Delta f = f_2$ than f_0, appears in the spectrum of the plasma oscillations. (The plasma has an inhomogeneous radial density distribution. When the probe is moved along the radius, the frequency f_1 varies in proportion to the density variation.) The decay condition $f_0 = f_1 + f_2$ is satisfied in a wide range of variation of f_0. The effective energy transfer to the low-frequency oscillations takes place at $2\pi f_2 = 2\times 10^6$ sec^{-1}, which corresponds to the frequency of the ion-acoustic oscillations (the masured electron temperature is $T_e = 50$ eV, $k^s{}_\phi = 1$, $\omega_s = k^s{}_\phi u_s = \sqrt{T_e/m_i} \simeq 2\times 10^6$ sec^{-1} $\simeq 2\pi f_2$). In this case, powerful ion-cyclotron oscillations are excited with frequency $2\pi f_{Hi} = eH/m_i c$ (see Figs. 1b and 2, IIb). The decay conditions $f_2^{st} = f_2 \pm f_{Hi}$ are satisfied also for the low-frequency spectrum (f_2^{st} are the frequencies of the "red" and "violet" satellites of the ion sound).

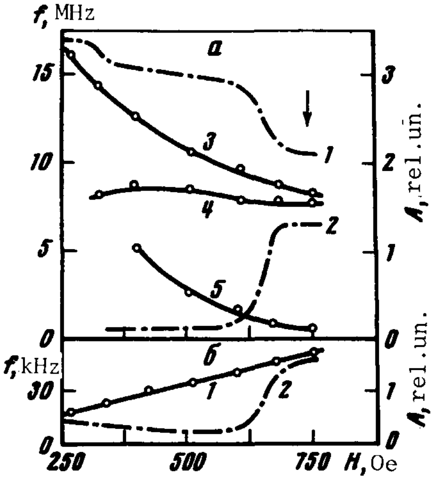

Fig. 1. Amplitude A and frequency f of the plasma oscillations vs. the magnetic field intensity H: a — amplitudes of the pump wave (1) and of the ion Langmuir oscillations (2), and the frequencies f_0 (3), f_1 (4), and f_2 (5); b — frequency (1) and amplitude (2) of ion-cyclotron oscillations.

An important feature of the spectra of the combination frequency is their asymmetry. The predominance of the amplitude of the "red" satellites in the HF and LF spectra is evidence of plasma instability with respect to low-frequency oscillations [8].

We measured the energy spectra of ions escaping from the plasma along the magnetic field direction in the case of developed resonant cyclotron instability [6] and in the case of the parametric excitation of ion waves (see Fig. 3). At cyclotron resonance, a small group of ions is effectively heated, and the particle energy distribution is almost Maxwellian. In the case of parametric excitation, on the other hand, of ion acoustic and gyroscopic oscillations, a plateau appears on the distribution function. This indicates that the average energy of the plasma ions is increased.

Experiments were performed also on excitation of parametric instabilities in a HF discharge plasma, when the pump field is produced by an external HF generator operating at a frequency close to ω_{LH}. In a HF discharge plasma with density $n = (2 - 3)\times 10^{10}$ cm^{-3} situated in a homogeneous longitudinal magnetic field, an alternating electrid field $\tilde{E} \perp H$ was produced with two semicylinders surrounding the plasma column. Starting with a certain critical HF power level, the pump wave is seen to decay into an ion-Langmuir wave ($2\pi f_1^* \simeq \omega_{pi}$) and an ion-acoustic wave ($2\pi f_2^* \simeq kv_s$) ($f_0^* =$

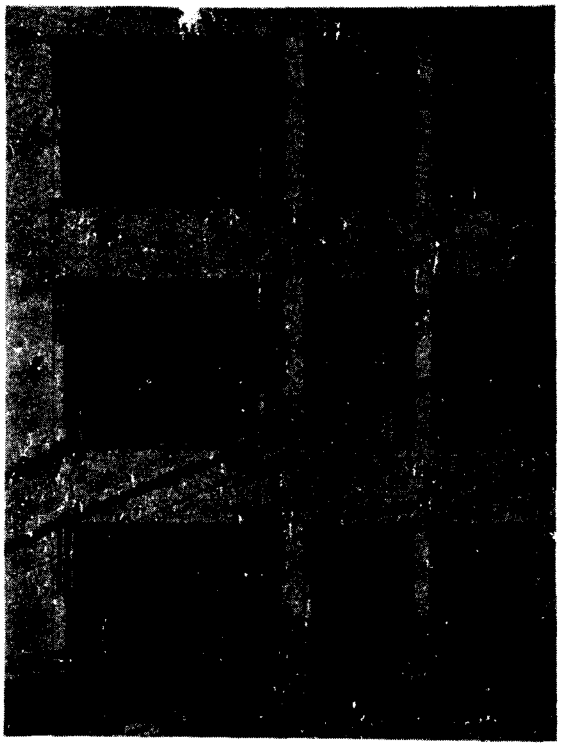

Fig. 2. Spectrograms of plasma oscillations in a discharge with oscillating electrons (a, b) and in a HF discharge plasma (c), obtained with an S4-8 spectrum analyzer: I — frequency spectra from zero to f_0, II — low-frequency part of spectra I, III — low-frequency part of spectra I (in the vicinity of f_0); a) $f_M = 11.5$ MHz, $f_0 = 10.4$ MHz, $f_1 = 8.1$ MHz, $f_2 = 2.3$ MHz, $f_{Hi} = 35$ kHz; $H = 500$ Oe, $U = 1.3$ kV, $P = 6\times10^{-5}$ mm Hg; b) $f_M = 8.5$ MHz, $f_0 = 8.2$ MHz, $f_1 = 7.8$ MHz, $f_2 = 0.4$ MHz, $f_{Hi} = 55$ kHz, $H = 700$ Oe, $U = 1.5$ kV, $P = 6\times10^{-5}$ mm Hg; c) $f_M = 11$ MHz, $f_0^* = 8.7$ MHz, $f_1^* = 8.2$ MHz, $f_2^* = 0.5$ MHz, $f_{Hi}^* = 105$ kHz, $H = 470$ Oe, $P = 6\times10^{-3}$ mm Hg, $n \simeq 10^{10}$ cm^{-3}. f_M is the frequency of the timing generator.

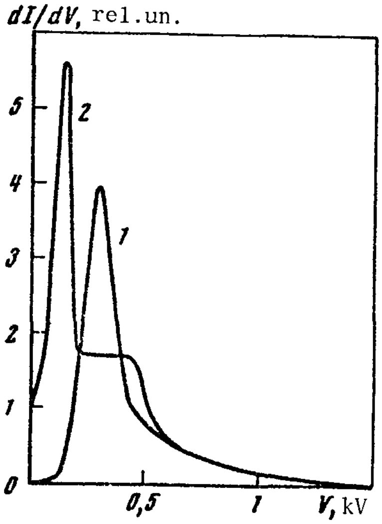

Fig. 3. Energy spectra of ions in cyclotron resonance (1) and in parametric excitation of ion cyclotron and acoustic oscillations (2). dI/dV is the derivative of the function I = f(V), where I is the electrostatic-analyzer collector current and V is the retarding potential.

$f_1^* + f_2^*$). Ion-cyclotron oscillations of frequency $2\pi f_{Hi}^* = 2(eH/m_ic)$ are observed in the low-frequency part of the spectrum.

In conclusion, the authors consider it their pleasant duty to thank Professor K. N. Stepanov, at whose initiative this research was performed.

[1] V. P. Silin, Usp. Fiz. Nauk 108, 625 (1972) [Sov. Phys.-Usp. 15, 742 (1973)].

[2] A. B. Kitsenko, V. I. Panchenko, K. N. Stepanov, and V. F. Tarasenko, 5th European Conf. on Contr. Fusion and Plasma Physics, Grenoble 1, 113 (1972); Zh. Tekh. Fiz. 42, 1996 (1972); 43, No. 7 (1973) [Sov. Phys.-Tech. Phys. 17, 1599 (1973); 18, No. 7 (1974)].

[3] A. A. Ivanov and V. V. Parail, Zh. Eksp. Teor. Fiz. 62, 932 (1972) [Sov. Phys.-JETP 35, 494 (1972)].

[4] J. M. Kindel, H. Okuda, and J. M. Dawson, Phys. Rev. Lett. 29, 995 (1972).

[5] W. M. Hooke and S. Bernabei, Phys. Rev. Lett. 29, 1218 (1972).

[6] A. M. Rozhkov, K. N. Stepanov, V. A. Suprunenko, V. I. Farenik, and V. V. Vlasov, Ukr. Fiz. Zh. 14, 1856 (1969); Plasma Phys. 12, 519 (1970).

[7] A. B. Mikhailovskii, Teoriya plazmennykh neustoichivostei (Theory of Plasma Instabilities), Atomizdat, 1970, Vol. 1.

[8] B. N. Rutkevich, Nelineinye volny v plasme (Nonlinear Waves in a Plasma), Kharkov State Univ. Press, 1973.