Certain results of investigations of nonlinear effects in the *E* layer of the ionosphere

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Defects of strong self-action of a high-power radio pulse and of deep cross modulation of trial waves in the lower layers of the ionosphere are described.

This is a report of certain results of the investigation of nonlinear effects produced in vertical sounding of the lower ionosphere by high-power radio pulses. The measurements were performed in 1961—1968 with apparatus whose parameters are described in a paper by the author.[1] The study was devoted to the self-action of a high-power pulse in the ionosphere and its interaction with other pulsed and continuous radio waves.

It must be emphasized that earlier investigations of nonlinear phenomena in the lower ionosphere were carried out at relatively low powers, when the wave field amplitude E was lower than the characteristic plasma field[2] E_p at which considerable nonlinear effects appear. In the present experiment, to the contrary, the maximum transmitter power ensured the production of an electric field $E \sim 10E_p$ in the lower layers of the ionosphere. In such strong fields, nonlinearity exerts a decisive influence on the radio wave propagation.[2]

The self-action effect manifests itself in a change of the absorption and in a distortion of the shape of the envelope of the radio pulse reflected from the ionosphere. This is seen from Fig. 1, which shows characteristic photographs of the radiated radio pulse (left) and that reflected from the ionosphere (right) at different radiation powers, obtained in daytime for the ordinary wave. The vertical strips in the figure are time markers spaced 10^{-4} sec apart and progressing from left to right. The amplitudes of the radiated and reflected radio pulses are presented in different scales (the former is artificially stressed). The radiation power increases by approximately 10 dB from Fig. 1a to Fig. 1c. The pictures show clearly the strong nonlinear distortion of the wave form of the reflected pulse.

The point is that the initial part of the pulse (up to the reflection point) propagates in an unperturbed or weakly perturbed ionosphere, since the ionosphere cannot change significantly within a time shorter than 10^{-4} sec. At $t \gtrsim 10^{-4}$ sec the amplitude of the reflected pulse varies with time, owing to the changes produced in the ionospheric plasma, and after a time $t \sim 2\times 10^{-4}$ sec it assumes a near-stationary level. This change in the

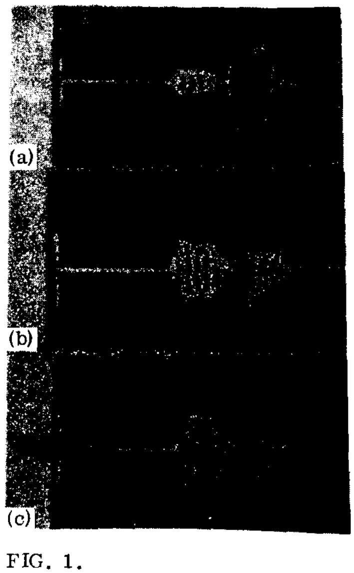

FIG. 1.

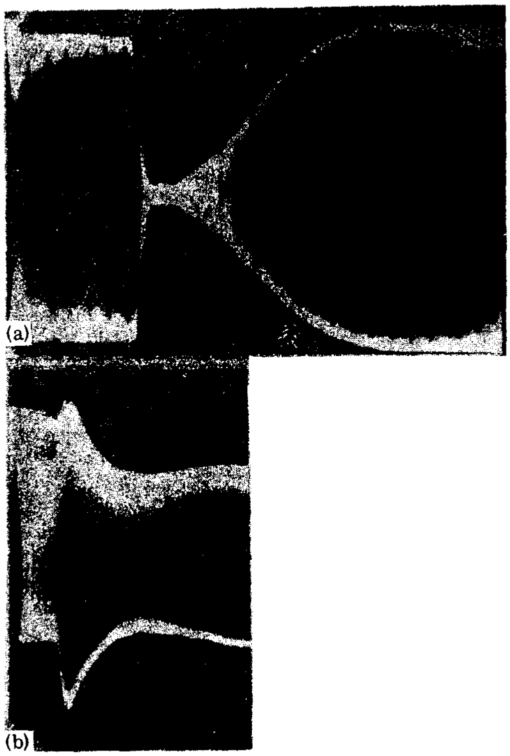

FIG. 2.

pulse amplitude is the consequence of the self-action of the pulse. With increasing radiated power, the self-action effects become stronger. As seen from Fig. 1, the stationary level of the signal reflected from the ionosphere does not increase in this case, and more readily decreases with increasing radiation power, thus exhibiting "saturation."

The additional nonlinear absorption of the ordinary wave at the maximum radiation power during daytime reached 20 dB and ~4–5 dB in the nighttime (the radiated power was approximately 3 dB lower than the maximum). For the extraordinary wave, at not too high power (less than – 10 dB from the maximum) its absorption, to the contrary, decreased with increasing radiation power—effect of "transparentization" of the plasma.

We investigated the interaction of the high-power pulse with continuous radiowave at frequencies $f^{(1)} = 254$ kHz and $f^{(2)} = 394$ kHz. A strong change in the amplitudes of the waves $f^{(1,2)}$ under the influence of the high-power pulse was observed. Thus, at the maximum power of the perturbing pulse, the amplitude of the $f^{(2)}$ wave was attenuated by a factor 10–20, corresponding to a nonlinear absorption of 20–25 dB–a "suppression" effect. This effect is illustrated in Fig. 2a, which shows the time variation of the amplitude of the wave of frequency $f^{(2)}$. The black strip on the horizontal axis of Fig. 2 denotes the time of action of the perturbing transmitter. We see that the $f^{(2)}$ wave is suppressed and has a prolonged relaxation period. At the frequency $f^{(1)}$, under certain conditions, we observe, to the contrary, amplification of the reflected wave under the influence of the high-power transmitter, or "transparentization" of the plasma (see Fig. 2b).

We note that in the case of interaction of two continuous waves, even though the radiation power is much lower than under pulsed conditions, a deep cross modulation wave observed, accompanied by strong distortion of the modulation waveform and even by a doubling of the modulation frequency—a "overmodulation" effect. The appearance of deep amplitude modulation of the useful wave under the influence of the perturbing transmitter and the onset of the "overmodulation" are illustrated in Fig. 3.

The cross modulation of short pulses, i.e., the interaction of a high-power pulse with another pulse of frequency f and duration 10^{-4} sec was investigated in a wide frequency range, $f = 0.5$–6 MHz. At the frequencies $f \lesssim 1$–2 MHz, the depth of the cross modulation reached 90% in daytime and evening time, and in the after-midnight hours it dropped to 10–30%. With increasing frequency f, the cross-modulation depth decreased. However, even at maximum frequencies, $f = 5$–6 MHz, it reached 30–40% in daytime. The depth of the cross modulation exhibited a strongly nonlinear dependence on the power of the perturbing station and considerable irregular variation with time.

The observed effects of self-action and interaction of radiowaves, including the qualitative "saturation," "transparentization," "suppression," and "overmodulation" effects are in good agreement with the results of theoretical calculation[2] in which account is taken of the variation of the electron collision frequency in the ionosphere as a result of the electron heating in the field of the high-power radio pulses. A comparison with theory shows that in the performed experiment the electron temperature in the lower ionosphere, at altitudes 80–100 km, was increased ~10–20 times by the high-power pulse.

During the time of action of the high-power transmitter, we observed a noticeable increase in the fre-

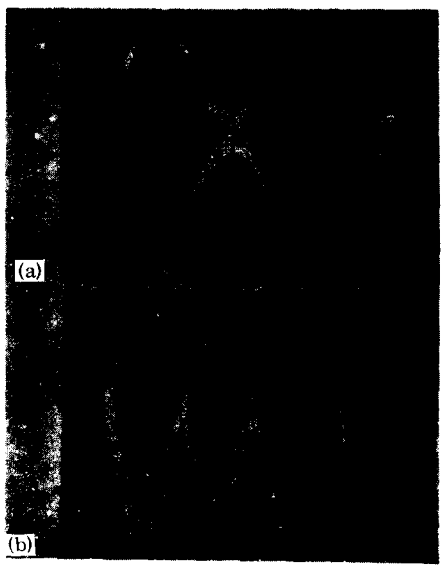

FIG. 3.

of the radio waves reflected from the nonlinear ionosphere, and this can be interpreted as the production of additional artificial ionization in the sporadic layer E_s. The frequency of the appearance of reflections from the sporadic layer also increased in this case.

In conclusion, the author considers it his pleasant duty to thank A.V. Gurevich for a useful discussion of the work and V.V. Vas'kov for help.

I. S. Shlyuger, ZhETF Pis. Red. 19, 274 (1974) [JETP Lett. 19, 162 (1974)].

[2]A. V. Gurevich, Radiotekhnika i élektronika 1, 706 (1956); V. L. Ginzburg and A. V. Gurevich, Usp. Fiz. Nauk 70, 201, 393 (1960) [Sov. Phys.-Usp. 3, 115, 175 (1960)]; A. V. Gurevich and A. B. Shvartsburg, Nelineĭnaya teoriya rasprostraneniya radiovoln v ionosfere (Nonlinear Propagation of Radiowaves in the Ionosphere), Moscow, Nauka, 1973.