A. G. Litvak. Self-Focusing and Waveguide Propagation in a Plasma. It is well known that the first studies on the theory of self-focusing of waves were devoted to a discussion of the features of this phenomenon in a plasma[1,2]. However, in connection with the rapid development of laser technology, the emphasis in the research has shifted to the optical band, as is evidenced in particular also by the papers presented at this session. At the same time, theoretical studies of self-focusing waves in plasma were continued at the Radiophysics Research Institute, followed by the first experiments aimed at observing this phenomenon. In this paper we report some of the results of these studies.

In phenomena involving self-action of electromagnetic waves in a plasma, one can separate two fundamentally different limiting cases: quasioptical self-focusing of waves in a transparent weakly-linear plasma, and effects of self-trapping of waves in an opaque plasma. Of course, the intermediate case of a strongly-nonlinear transparent medium can also be realized in experiment.

The simplest and best investigated is the propagation of broad beams (in terms of the wavelength) in a medium with weak nonlinearity $\epsilon = \epsilon_0 + \epsilon' f(|\mathbf{E}|^2)$, $\epsilon' f(|\mathbf{E}|^2) \ll \epsilon_0 = 1 - (\omega_p^2/\omega^2)$. In this case one can use the parabolic-equation method employed in nonlinear optics, and many of the results of the optical theory of self-focusing of waves turn out to be valid also for a plasma. The specific features of the plasma become manifest in the concrete $\epsilon(\mathbf{E})$ dependences, which are connected with the plasma mechanisms of nonlinearity. The principal role is played here by inertial mechanisms that lead to a decrease in the plasma concentration in the region of the field—striction and heating (both ordinary ohmic and anomalous heating connected with processes of wave interaction in a collisionless plasma). Allowance for the saturation of the nonlinearity turns out to be a major factor that contributes to the waveguide character of the propagation. To the contrary, realization of the multifocus structure of self-focusing[6] in a plasma is made difficult by the fact that the effects of multiphoton absorption in the plasma are usually negligibly small. A detailed analysis of the plasma nonlinearity mechanisms, the processes of their relaxation, and the features of self-focusing in an isotropic and magnetoactive plasma shows that effects of quasioptical self-focusing can play an important role not only in the interaction between microwave radiation of moderate intensity with a laboratory plasma and in laser breakdown, but also under natural conditions, when powerful radio waves of the short-wave and infralow frequency bands propagate in the earth's ionosphere and magnetosphere[3b].

The calculations were used as a basis for the development of installations for experimental study of thermal self-focusing of microwaves in a weakly ionized plasma (this effect is characterized by the smallest critical power and should therefore not be accompanied by other nonlinear processes that usually complicate the observed picture). The results[4,5] are evidence of observation of nonstationary self-focusing and is in good agreement with the theory. The results of one of the experiments (λ = 0.5 cm, unfocused beam)[4] can be interpreted with the aid of the concept of moving focus; in the other experiment (λ = 3 cm, focused beam)[5], the nonlinear nonstationary effects became manifest only near the focus and led to a decrease in the focal dimension of the beam without a change in its coordinate (collapsing focus).

Another limiting case of self-action of waves in a plasma is connected with the possible propagation of intense waves in a medium this is not transparent in the linear approximation. The "bleaching" of a non-transparent plasma by an incident wave is a result of a redistribution of the charge particles in the plasma and formation of a waveguide (rarefied) channel. This phenomenon of self-channeling of the wave differs in principle from the quasioptical self-focusing in a transparent medium, in which the nonlinearity is not the cause of the wave propagation, and leads only to elimination of the diffraction divergence of the beam and of the refraction. A theoretical investigation of self-channeling is a more complicated problem, for in this case the weak-nonlinearity approximation no longer holds, and in addition, the problem is not scalar, i.e., the equations depend on the type of polarization of the electromagnetic waves.

Certain features of self-channeling of waves can be explained already by investigating channels that are homogeneous in the propagation direction. Two-dimensional and axially-symmetrical TE waves were considered in[3,7]. A study of waveguides formed by PM waves encounters fundamental difficulties because the solution has singularities in the region of plasma resonance $\omega \approx \omega_p$. It was shown in[3a] that the field equations have no localized solution in the class of continuous functions if no account is taken of the spatial dispersion, and it is necessary to construct a discontinuous solution in which, just as in a quasistatic field[8], the passage through the resonance region takes place jumpwise. Of course, to determine the microstructure of the jump it is necessary to take into account the spatial dispersion (to raise the order of the system of equations) and the dissipation of the plasma waves excited in the region of $\epsilon = 0$. The attempt in[9] to construct an analytic solution without a discontinuity was made without taking into account the existence of singular points on the integral curves.

Effects of self-channeling of microwaves in a plasma were observed in experiments performed at the Radiophysics Research Institute and at the Physics Institute of the USSR Academy of Sciences[10]. These experiments confirmed the importance of this phenomenon and stimulated further development of its theory. In particular, to explain the experimental results, the problem of the stability of reflection of a homogeneous plane wave from an opaque plasma was considered. It was shown that a homogeneous skin layer is unstable to space-time disturbances, since this instability can lead to the formation of a set of waveguide channels in the opaque plasma.

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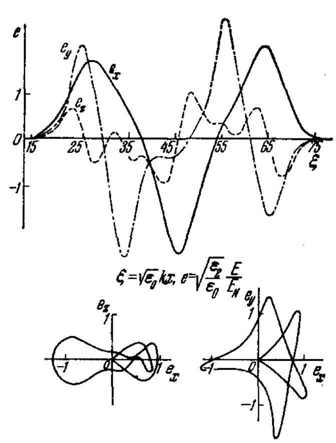

FIG. 1

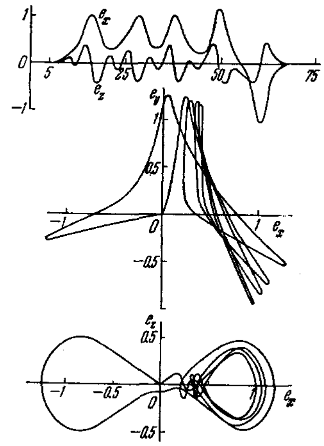

FIG. 2

V. M. Eleonskiĭ, L. G. Oganes'yants, and V. P. Silin. Vector Structure of Electromagnetic Field in Self-Focused Waveguides. Self-focused distributions of the electromagnetic field in nonlinear media were first investigated theoretically in[1]. Progress from the simplest single-component structure of the localized field to more complicated ones was made in recent years[2,3]. Field structures up to general three-component type have by now been investigated.

The equations of nonlinear electrodynamics (see[3]) admit of solutions $E(x)\exp(ik_z z)$ in the case of planar geometry, and make it possible to separate two types of exact solutions with single-component $(0, E_y, 0)$ and two-component $(E_x, 0, E_z)$ electric vectors, as well as the more general case of three-component solutions (E_x, E_y, E_z). The system of equations of nonlinear electrodynamics includes the conservation law

$$H=P^2-k_z^2E_y^2+[(k^2\varepsilon-k_z^2)^2-k_z^4]\,k_z^{-2}E_x^2+k^2\int\limits_0^{E^2}\varepsilon(q)\,dq,$$

where $k = \omega/c$, $P = d\dot{E}_y/dx$, and $\epsilon(E^2)$ the nonlinear dielectric constant. This makes it impossible to determine in the space (E_x, E_y, E_z) at $H = 0$, which is essential for self-channeling, a boundary surface $P(E_x, E_y, E_z) = 0$ inside of which all the localized solutions are located. The boundary conditions for the self-channeling fields are

$$\lim_{E\to 0}(E_z/E_x)=\pm[k_z^2-k^2\varepsilon(0)]^{1/2}\,k_z,\quad \lim_{E\to 0}(E_y/E_x)=C,$$

where C is a parameter of the problem proper. A qualitative analysis and numerical integration indicate that there exists a sequence of three-component fields localized in space. The results of a numerical integration, performed for $\epsilon = \epsilon_0 + \epsilon_2 E^2 E_N^{-2}$, are shown in Figs. 1 and 2, where the projections of the electric-vector motion are shown together with the spatial distribution of the field. The self-channeling three-component fields are characterized by a unique structure with low symmetry. The localization region of the obtained self-channeling waveguides exceeds the characteristic dimension of the localization region of the one- and two-component states by several times. However, the largest projections E_y and E_x, E_z for the three-component localized states do not exceed the largest values of the corresponding projections for the localized one- and two-component states. The reason is that the characteristic dimensions of the boundary surface $P(E_x, E_y, E_z) = 0$, which is a degenerate torus, are determined by the parameters of one- and two-component localized states. Localized three-component states of the field can be ordered in accordance with the number of tangencies of the electric vector, which describes a closed curve in the space (E_x, E_y, and E_z), with the boundary surface. For example, for the states shown in Figs. 1 and 2, the number of tangencies between the entry and departure points of the 0-field regions is six and ten, respectively. A single-component localized state (waveguide of TE type) corresponds to one tangency, and a two-component state (waveguide of type TM) corresponds to motion over a curve lying on the boundary surface. We note that three-component self-focused waveguides correspond to allowance for both the transverse and longitudinal degrees of freedom of the electromagnetic field.

In the case of cylindrical geometry, the equations of nonlinear electrodynamics admit of solutions $E(\rho)\exp(ik_z z + im\varphi)$. At $m = 0$, i.e., for fields that do not depend on the azimuthal angle, it becomes possible to separate not only two types of exact solutions with one- and two-component vectors $(0, E_\varphi, 0)$ and $(E_\rho, 0, E_z)$, but also a more general three-component solution (E_ρ, E_φ, E_z). A feature of such a three-component solution is that at $m = 0$ the connection between the electric-vector projections E_φ, E_ρ, and E_z is only via a nonlinearity, namely the dielectric constant. The problem is to find the eigenvalues of a pair of parameters, namely, the z-projections of the electric and magnetic fields on the axis of the self-focused waveguide. Numerical integration leads to a three-component localized state with the field distribution shown in Fig. 3. The same figure shows the projections of the motion of the electric vector, characterizing the peculiar polarization structure of the electromagnetic field. We note that the characteristic dimension of the localization region in space, the characteristic values of the projec-