Optical anisotropy of a laser plasma

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The optical anisotropy of a laser plasma has been studied experimentally for the first time. At pump intensities $\sim 5 \times 10^{14}$ W/cm^2, the optical anisotropy in the region of the plasma with electron densities to $\sim 2 \times 10^{20}$ cm^{-3} is governed by spontaneous magnetic fields. Gradients of the electron density have no significant effect on the plasma anisotropy.

The space–time structure of the magnetic fields generated in a laser plasma is a topic of current interest in research on laser fusion. The interest arose because the megagauss-range magnetic fields observed in the experiments of Refs. 1–3 might have a strong influence on the interaction of intense laser light with matter. The most informative way to study magnetic fields in laser plasmas is to use the method based on the Faraday magnetooptic effect. Simultaneous measurements of the angle through which the polarization plane rotates, $\alpha \sim \int B n_e \, dl$, and the phase shift $\delta \sim \int n_e \, dl$ (B is the magnetic induction, n_e is the electron density, and l is the path length) of a probe electromagnetic wave make it possible to reconstruct the magnetic induction, averaged over the optical path length, with high spatial and temporal resolution.[4]

The Faraday effect is known to arise from a birefringence of an electromagnetic wave in a plasma, which results from a longitudinal magnetic field. In general, however, the birefringence of a wave in a plasma is a consequence of an anisotropy of its permittivity tensor, and it can arise in the absence of a magnetic field. Transverse gradients of the electron density, ∇n_e (Ref. 5), and of the temperature and velocity, ∇T and ∇v_e (Ref. 6), can thus give rise to a change in the polarization of a probe wave. An estimate in Ref. 6 shows that the gradients of the electron density, ∇n_e, have the greatest effect on the polarization of probe light under the conditions prevailing in a laser plasma. It should also be noted that the polarization plane of electromagnetic radiation rotates when the radiation is refracted in a plasma which is inhomogeneous in two dimensions; the magnitude of the rotation angle is inversely proportional to the radius of the twisting of the ray path.[7] However, in view of the speed of the optics used experimentally, this effect is negligible. Faraday measurements of magnetic fields thus require a preliminary determination of the nature of the optical anisotropy of the laser plasma. With this information, it becomes possible to estimate how gradient mechanisms alter the polarization of a probe electromagnetic wave. Although the study in magnetic fields in laser plasmas by means of the Faraday effect has been the topic of a fair number of experimental studies (e.g., Refs. 1–3), just how the polarization of probe radiation is affected by transverse gradients of the electron density remains an open question, casting doubt on the validity of the results which have been found.

In polarization measurements, the relative change in the light intensity beyond the analyzer is given by the Malus law, which can be written as follows if the changes in the angle through which the polarization plane is rotated, $\Delta\alpha$, and in the degree of ellipticity of the electromagnetic wave, Δk, are small [$k=(J_{\min}/J_{\max})^{1/2}$ is the ratio of the minimum and maximum amplitudes of the electric vectors of the polarization ellipse]:

$$\Delta J/J=\Delta\alpha^2+\Delta k^2+K_0, \tag{1}$$

where K_0 is the contrast of the polarimeter.

Let us consider the case in which a probe electromagnetic wave is propagating in a plasma at an angle β with respect to the (vector) magnetic induction. The electromagnetic radiation propagates through the plasma in the form of two elliptically polarized normal waves, which differ in phase velocity.[8] In this case the resultant state of the probe radiation is characterized by changes in both the polarization-plane rotation angle and the degree of ellipticity. Under the condition for "quasilongitudinal" propagation of the electromagnetic wave[8] (this condition imposes restrictions on β), the change in the polarization of the wave can be written as follows:[8]

$$\Delta\alpha=-\Delta\varphi_F/2, \quad \Delta k<(\Delta\varphi_{CM}/2), \tag{2}$$

where

$$\Delta\varphi_F=5.24\times10^{-17}\lambda^2\int^L (B\sin\beta)n_e dl,$$

$$\Delta\varphi_{CM}=2.47\times10^{-21}\lambda^3\int^L (B\sin\beta)^2 n_e dl$$

are the phase shifts (in radians) in the Faraday and Cotton–Mouton effects, respectively, λ is the wavelength in centimeters, B is the magnetic induction in gauss, n_e is the electron density in cm^{-3}, and L is the size of the plasma in centimeters. A comparison of the values of $\Delta\varphi_F$ and $\Delta\varphi_{CM}$ for the case in which a plasma is probed in the optical wavelength region, at λ =500 nm, with $B\sim0.1-1$ MG, shows that $\Delta\varphi_F$ is two or three orders of magnitude greater than $\Delta\varphi_{CM}$; i.e., the change in the ellipticity of the wave can be ignored in the case of quasilongitudinal propagation.

In a linearly anisotropic plasma (i.e., there is a transverse magnetic field or gradients of the electron density), the probe radiation propagates in the form of two plane-polarized normal waves. The polarization changes in the same way as in the propagation of light through a phase plate. At the small phase shifts ($\Delta\varphi_l\ll1$) characteristic of a laser plasma, the changes in the rotation angle and the degree of ellipticity of the resultant wave are given by[9]

$$\Delta\alpha=-\frac{1}{2}\sin(4\theta_0)(\Delta\varphi_l/2)^2, \quad \Delta k=\sin(2\theta_0)(\Delta\varphi_l/2), \tag{3}$$

where θ_0 is the angle between the initial direction of the polarization plane of the probe wave and the direction of the linear anisotropy of the plasma. The phase shift $\Delta\varphi_l$ depends on the particular mechanism responsible for the linear anisotropy of the plasma.

Analysis of expressions (1)–(3) shows that in the case of a linear anisotropy of the plasma (at small phase shifts) the change detected in the signal beyond the analyzer is due to a change in the ellipticity of the wave. If the plasma anisotropy is determined by a longitudinal magnetic field, the signal which is detected stems from a rotation of the polarization plane of the probe radiation. If a change in the rotation angle and a change in the ellipticity of the probe wave are detected simultaneously, the meaning is that either the longitudinal magnetic field and the transverse gradients of the electron density have comparable effects on the polarization or that there is an anisotropy of the absorption of circularly polarized normal waves in a magnetized plasma.[8] A change in the polarization of a probe electromagnetic wave can thus provide information on the mechanism responsible for the change in polarization and thus about the optical anisotropy of the laser plasma.

An experiment was carried out at the Feniks high-power, single-beam Nd laser[10] with a wavelength of 0.527 μm, a pulse length $\sim$ 1.5 ns, an energy $\leqslant$ 10 J, and a flux density $\leqslant 5 \times 10^{15}$ W/cm^2 at the focus. The pump light was focused on the surface of a flat aluminum target in a spot $\sim$ 15 μm in diameter with the help of a two-component objective lens with an aperture ratio 1:6. The probe light was generated by tapping part of the pump beam and doubling its frequency in a KDP crystal.

A three-channel polarimeter, whose optical layout is described in Ref. 11, was developed in order to measure the polarization of the probe electromagnetic wave. This polarimeter was capable of measuring the polarization-plane rotation angle α and the depolarization coefficient K ($K = J_{\min}/J_{\max}$). It provided a spatial resolution $\sim$ 5 μm and a contrast $K_0 = 1.2 \times 10^{-4}$. Three images of the laser plasma were formed in one laser shot: two Faraday images F_1 and F_2 and one shadow image T. The orientation of the analyzers in the F_1 and F_2 channels with respect to the entrance polarizer was chosen in such a way that the transmission directions of these analyzers did not make right angles with the crossing angle $\pm\alpha_0$ (where α_0 is the optimum crossing angle[4]). In our experiments this optimum angle was $\alpha_0 = 5°$. Calibrated RF-3 photographic film was used as detector. The coordinate scales for the three images of the laser plasma were reconciled with the help of a visualizing diaphragm in an intermediate image of the plasma. Experiments were carried out for two inclinations of the transmission direction of the entrance polarizer with respect to the normal to the target surface: $\theta_0 = 0$ and 45°.

Figure 1 shows images of the laser plasma obtained in the three polarimeter channels at a time 1 ns after the arrival of the pump light, for the angle $\theta_0 = 0$. The energy of the laser radiation was $E = 5.3$ J. On the images F_1 and F_2 (in contrast with the shadowgram T) we can see a modulation of the light intensity near the region in which the plasma is opaque. This modulation indicates that polarization changes occurred with the probe beam in these regions of the plasma.

Figure 2 shows the results of a reconstruction of the polarization-plane rotation

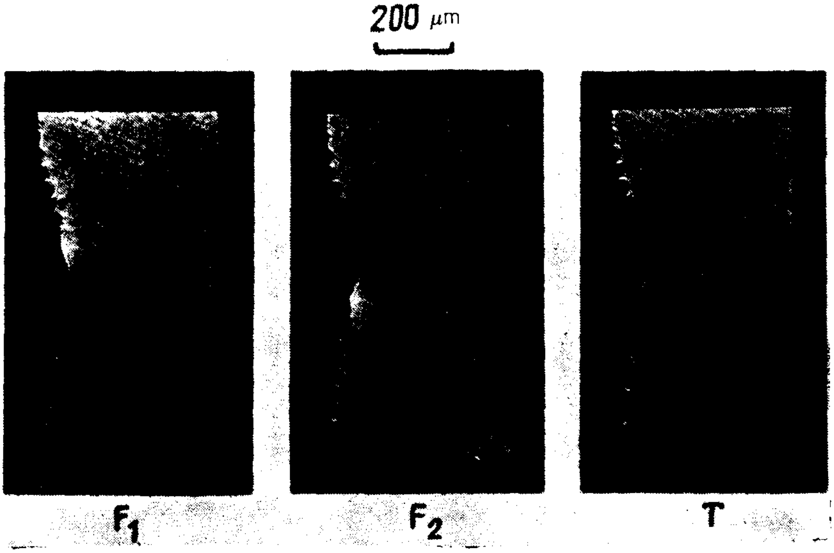

FIG. 1. Faraday images (F_1, F_2) and shadow image (T) of a laser plasma taken 1 ns after the arrival of the pump light. The cross-hatching angles are $\alpha_{01}=+5°$ and $\alpha_{01}=-5°$ for the F_1 and F_2 channels, respectively.

angle α (r) (Fig. 2a) and of the depolarization coefficient $K(r)$ (Fig. 2b) of the probe radiation at a distance $Z=75$ μm from the target surface. The $K(r)$ profile differs from the α (r) profile in being noisy, since in the interval from 0 to 240 μm (in which α can reliably be detected) the shape and level of this profile are essentially the same as in the interval 240–400 μm (where α is measured at the noise level). The average depolarization of the probe wave over the cross section is $K\sim 2.6\times 10^{-4}$, or roughly twice K_0. This "uniform" depolarization along the cross section is the result of an effect of

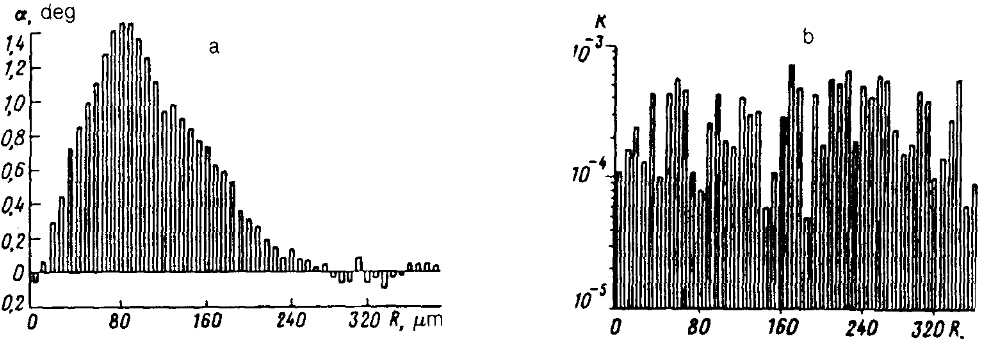

FIG. 2. a—Profile along the target surface in the cross section $Z=75$ μm of the angle through which the polarization plane of the probe light is rotated, α (r); b—profile along the target surface in the cross section $Z=75$ μm of the depolarization coefficient of the probe light, $K(r)$.

uncorrelated noise associated with the high coherence of the probe beam in the polarimeter channels. Analysis of interferograms of the laser plasma recorded in some separate shots revealed that the probe radiation penetrated into the plasma to a region of density $n_e \sim 2 \times 10^{20}$ cm $^{-3}$.

Corresponding α (r) and $K(r)$ profiles were measured in experiments with an $\theta_0 = 45°$. The idea behind this experiment was that, if the optical anisotropy of the plasma were determined by gradients of the electron density, then the values of α and K should have depended on the angle θ_0, and under the conditions prevailing in the laser plasma the depolarization should have reached a maximum at $\theta_0 = 45°$. The reason for the latter assertion is that the macroscopic gradients of the temperature, ∇T_e, and the electron density, ∇n_e, are directed basically along the target surface and across it, respectively. However, the distribution of the depolarization coefficient was noisy, as in the $\theta_0 = 0$ case. In all the experiments, the direction in which the polarization plane of the probe light rotated corresponded to a toroidal structure of the magnetic fields, associated with an electron current flowing along the axis of the pump beam toward the target.

These measurements showed that under the conditions of these experiments the Faraday magnetooptic effect is the dominant mechanism for the change in the polarization of the electromagnetic wave. At a pump intensity $\sim 5 \times 10^{14}$ W/cm^2 in the region of the plasma with electron densities to $\sim 2 \times 10^{20}$ cm^{-3}, the optical anisotropy of the laser plasma is thus governed by the presence of longitudinal magnetic fields in the plasma. The gradients of the electron density turn out to have an insignificant effect on the plasma anisotropy.

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