S- and p-polarized reflectivities of strongly correlated plasma

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Abstract. An analysis of the response of a dense plasma to electromagnetic waves of moderate intensity can be used as a tool to study the validity of physical models describing the behavior of matter in extreme conditions. Within this work, the new experimental data are presented on oblique incidence of polarized electromagnetic waves. The study of polarized reflectivity properties of nonideal xenon plasma was accomplished using laser light at \( \nu_{\text{las}} = 2.83 \times 10^{14} \text{ s}^{-1} \). The measurements of polarized reflectivity coefficients of explosively driven dense plasmas have been carried out at incident angles up to \( \theta = 70^\circ \) for plasma density \( \rho = 1.8 \text{ g/cm}^3 \). The simple model of the ionization kinetics of the plasma transition region is considered.

1. Introduction

The investigation of the properties of the electronic subsystem of warm dense matter remains an urgent problem in high-energy-density physics. Because the light electrons can be controlled with low energies and make a significant contribution to physically observable phenomena, such as electrical conductivity or optical properties controlled by the dielectric function, the description of the electronic subsystem is of great interest. The study of the polarization properties of a warm dense matter is an important diagnostic tool for the study of strongly nonideal plasma. The analysis of the reaction of dense plasma to electromagnetic waves of moderate intensity can be used as a tool to study the reliability of physical models describing the behavior of matter under extreme conditions, high temperatures and pressures. Of particular interest are optical polarization measurements of materials in which a transition from a dielectric to a metal-like state occurs with increasing density due to pressure ionization.

Ionization kinetics describes the time evolution of the ionization degree within a chemical picture, where free electrons and electrons bound in neutral atoms are treated as different species. Already in [1], it has been argued, that due to microscopic processes, the plasma front is far from being step-like. Plasmas created have transitive surfaces with a density profile. At densities typical for the warm dense matter, density effects such as screening, ionization potential depression [2] and Pauli blocking have a strong influence on the formation of the plasma density profile.

Previously, we measured the reflection coefficients for a fixed-frequency laser beam at the plasma front [1, 3–6] and used the experimental data to preliminarily adjust the parameters density profile. Extension of experimental conditions to find the angular dependence of s- and...
p-polarized reflectivities at several wavelengths can be used to construct the spatial profile of the density of charge carriers in more details. It is important to interpret the experimental data correctly as the small changes of layer parameters cause the considerable variations of the total reflectivity of shock-compressed plasma.

In this paper, we report new results of s- and p-polarized reflectivity measurements of nonideal plasma at $\nu_{\text{las}} = 2.83 \times 10^{14}$ s$^{-1}$ ($\lambda_{\text{las}} = 1064$ nm).

2. Measurement technique and results
A study of the polarization reflective properties of strongly correlated plasma was carried out using the method of oblique sounding by polarized electromagnetic waves. To study the optical properties of shock-compressed plasma, we used a laser diagnostic system [7], which has been significantly upgraded. The following components were improved or redesigned: the light pump system of a probe laser, the correction block of an electro-optic shutter activation system, the ionization sensor of a shock front position. The shape of aspherical lenses were recalculated. The modernization was aimed at improving the stability of the system, the timing accuracy of all involved processes and the reliability of the experimental data. The analysis of the angular distribution of the reflected energy from the plasma [8] allowed to improve the matching of the parameters of the receiving optics to the reflection indicatrix of the plasma object. In a special series of experiments the comparison of the lens receiving optics and optical fibers with the built-in strong anisotropy was carried out. Experiments have shown a much higher accuracy of measurement of the required physical characteristic using aspherical lenses.

To create a warm dense substance, we used shock waves generated by the explosion, which lead to the compression and irreversible heating of xenon. The pulsed $Y_3Al_5O_{12}:\text{Nd}^{3+}+\text{KTiOPO}_4$ laser system has been applied to measure the dense xenon plasmas polarized reflectivity coefficient. The Stokes vector components have been determined using the four-channel pulse high-speed device that measured the intensity of the reflected laser beam at four azimuthal angles and was equipped with filters to select the frequency of probing.
Table 1. Results of experiments for the s- and p-polarized reflectivities of explosively driven dense xenon plasma at $\nu_{\text{las}} = 2.83 \times 10^{14}$ s$^{-1}$ and thermodynamic parameter values: pressure $P$, temperature $T$, mass density $\rho$, free-electron number density $n_e$, density of neutral atoms $n_a$, ionization degree $\alpha_{\text{ion}} = n_e/(n_a + n_e)$, nonideality parameter $\Gamma$ and degeneracy parameter $\Theta$.

| $\theta$ | $R_s$  | $R_p$  | $P$, GPa | $T$, K  | $\rho$, g/cm$^3$ | $n_e$, cm$^{-3}$ | $n_a$, cm$^{-3}$ | $\alpha_{\text{ion}}$ | $\Gamma$ | $\Theta$ |
|--------|--------|--------|----------|--------|------------------|----------------|----------------|----------------|--------|--------|
| 0$^\circ$ | 0.25   | 0.25   |          |        |                  |                |                |                |        |        |
| 10$^\circ$ | 0.28   | 0.24   |          |        |                  |                |                |                |        |        |
| 15$^\circ$ | 0.32   | 0.21   |          |        |                  |                |                |                |        |        |
| 20$^\circ$ | 0.39   | 0.22   |          |        |                  |                |                |                |        |        |
| 25$^\circ$ | 0.41   | 0.17   |          |        |                  |                |                |                |        |        |
| 30$^\circ$ | 0.55   | 0.18   |          |        |                  |                |                |                |        |        |
| 35$^\circ$ | 0.52   | 0.21   | 9        | 28500  | 1.80             | $5.0 \times 10^{21}$ | $6.1 \times 10^{21}$ | 0.46       | 1.4    | 1.7    |
| 40$^\circ$ | 0.58   | 0.13   |          |        |                  |                |                |                |        |        |
| 45$^\circ$ | 0.595  | 0.2    |          |        |                  |                |                |                |        |        |
| 50$^\circ$ | 0.69   | 0.17   |          |        |                  |                |                |                |        |        |
| 55$^\circ$ | 0.67   | 0.27   |          |        |                  |                |                |                |        |        |
| 60$^\circ$ | 0.72   | 0.32   |          |        |                  |                |                |                |        |        |
| 65$^\circ$ | 0.725  | 0.53   |          |        |                  |                |                |                |        |        |
| 70$^\circ$ | 0.85   | 0.58   |          |        |                  |                |                |                |        |        |

The previously obtained experimental data were used to modernize the explosive generator of warm dense matter. In figure 1, one can see the upgraded explosive system of generation of the dense plasma. This system (for example, unlike laser systems) is characterized by the absence of disturbing electromagnetic fields and comparative simplicity of obtaining one-dimensional gas-dynamic flow.

The thermodynamic parameters including the composition of the plasma were determined from the measured shock wave velocity in connection with appropriate equation of states using the Saha IV code [9–11]. The results of our experiments at $\nu_{\text{las}} = 2.83 \times 10^{14}$ s$^{-1}$ together with the thermodynamic parameters of the studied dense plasma are presented in table 1.

3. Analysis

The reflectivity of the xenon plasma for s- and p-polarization can be derived from the solution of Maxwell equations containing the dielectric function. In turn, the dielectric function of the medium, written in the form of the generalized Drude expression [12] depends on the collision frequency of particles. The warm dense matter contains strongly interacting charged particles that play a critical role in such a medium and can be adequately described on the basis of quantum statistical theory. According to the Matthiessen rule, the total collision frequency is the sum of the contributions owing to the different scattering processes, the electron–ion and the electron–atom collisions. In our work we calculated the dynamic collision frequency of charged particles in the Born approximation for the Coulomb potential [13]. The contribution of collisions with neutral Xe atoms was taken into account by the factor $f$ as $\nu_{\text{ca}}(n_e, n_a, T) = f \nu_{\text{ci}}(n_e, n_i, T)$, where $\nu_{\text{ca}}(n_e, n_a, T)$ is frequency of the electron–atom collisions, $n_e$, $n_a$, and $n_i$ are the electron, atom, and ion density, accordingly, $\nu_{\text{ci}}(n_e, n_i, T)$ is frequency of the electron–ion collisions, $T$ is temperature. The factor $f$ was calculated by solving the variational problem.

Figure 2 presents both the new experimental data and the data obtained earlier for the laser frequency $\nu_{\text{las}} = 2.83 \times 10^{14}$ s$^{-1}$ ($\lambda_{\text{las}} = 1064$ nm) and the plasma density $\rho = 1.8$ g/cm$^3$. It
Figure 2. S- and p-polarized reflectivity indexes of strongly correlated dense plasma calculated in comparison to the experimental data for laser light at $\nu_{\text{las}} = 2.83 \times 10^{14}\text{ s}^{-1}$: $L$ is the width of the plasma transition region. The $R_{s}^{\text{calc}} L = 290\text{ nm}$ curve and the $R_{p}^{\text{calc}} L = 290\text{ nm}$ curve are from the calculations without new points. Also shows the results of new calculations using an improved procedure for solving variational problems in which Fermi-like profile [14] for a free electron density in shock wave front was used. The calculations without the use of new experimental points (similar to work [7]) and the comparison of results for the Fermi-like profile with the step-like profile (Fresnel formula) are shown in the figure 2 too.

As a result of our calculations, the parameters of the transition layer of dynamic plasma were found. The following values of the fitting parameters $A = 0.018$, $B = 1.09$ and the width of the plasma transition region $L = 270\text{ nm}$ are obtained, which differ somewhat from the results of work [7] with fewer points ($A = 0.022$, $B = 1.01$ and $L = 290\text{ nm}$) and better describe the experiment (the sum of squared deviations is smaller).

Using the ideology of paper [15], it is possible to construct a simple model of ionization kinetics in the plasma transition region and to obtain an equation for the electron density profile

$$\alpha_e[kn_e^2(z) + n_e^2(z) - (n_e^{\text{pl}} + n_t^{\text{pl}})n_e(z)] = -v\frac{dn_e(z)}{dz},$$

(1)

where $\alpha_e$ is an ionization coefficient, $k = n_e^{\text{pl}}/(n_e^{\text{pl}})^2$, $v$ is a shock front velocity. Collating the solution of the ionization kinetic model (1) to the Fermi-like profile, we obtained an ionization coefficient $\alpha_e = 6.7 \times 10^{-18}\text{ m}^3/\text{s}$ for the plasma density $\rho = 1.8 \text{ g/cm}^3$. 

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4. Conclusions
The data from such experiments is an important cornerstone to construct theoretical models for the description of warm dense matter. In this paper, we present the results of new experiments on reflectivity of polarized light on shock-compressed plasma with strong interparticle interaction. By numerically solving Maxwell equations with a new set of experimental data for plasma density $\rho = 1.8 \text{ g/cm}^3$, we obtained almost identical parameters of the transition layer of the dynamic plasma. It confirms the correctness of the physical model of warm dense matter-electromagnetic field interaction.

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