The interaction of laser radiation with strongly coupled plasmas

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Abstract. New results of measurements of s- and p-polarized reflectivity of nonideal plasma at the frequency of the external electromagnetic field $\nu_{\text{las}} = 2.83 \times 10^{14} \text{ s}^{-1}$, free-electron number density $n_e = 3.3 \times 10^{21} \text{ cm}^{-3}$ (Coulomb nonideal plasma parameter $\Gamma = 1.2$) and $n_e = 5.2 \times 10^{21} \text{ cm}^{-3}$ ($\Gamma = 1.4$) are presented. These data are the result of the next stage of study of optics of a warm dense matter. We present a microscopic approach to describe the entire set of experimental data on the optics of strongly correlated plasma.

1. Introduction
The presence of significant difficulties in the theoretical description of dense plasma with strong interaction of particles leads to the need to obtain as much experimental information about the optical and transport properties of such a medium as possible. It should be noted that the study of optics of a dynamic object is a powerful research tool, since optical properties are very sensitive to changes in the electronic subsystem of substance. At the same time, experimental physical studies allow us to discover the applicability of existing theoretical models, and are also used to determine the numerical parameters of functional dependencies describing the behavior of warm dense matter and developed on the basis of strict asymptotic solutions for weakly nonideal medium [1–4].

Already in [5], it has been suggested that microscopic processes lead to blurring of the shock wave front more than is commonly believed. The works [6–9] describe experiments in which the reflective properties of plasma under inclined probing are studied. Since the test electromagnetic wave during propagation through the plasma is attenuated by absorption, the experimental data can be used to determine the geometric parameters of the transition layer in solving the field equations.

The following are the results of the next phase of the study of plasma optics at free-electron number density $n_e = 3.3 \times 10^{21} \text{ cm}^{-3}$ and $n_e = 5.2 \times 10^{21} \text{ cm}^{-3}$, complementing the database on reflective properties of plasma obtained by us earlier and which is necessary to create physically adequate models of the permittivity function of a strongly correlated medium.

2. Measurement technique
The hydrodynamic method traditionally used at the Institute of Problems of Chemical Physics of the Russian Academy of Sciences was applied to generate the required plasma states. To create
vacuuming and gas supply
ionization sensor
thermostat
cable
direction of striker movement

**Figure 1.** The modified gas cell with a striker block.

We utilized explosive shock waves that lead to compression and irreversible heating of the inert gas. The detonation products of the explosive accelerate the metal striker to a speed of 5 km/s, followed by its collision with an experimental cell filled with xenon. In this case, an intense shock wave is created in the studied gas. Figure 1 shows a modified gas cell designed to operate at high angles of interaction between plasma and probing radiation. Control of flatness and homogeneity of a dynamic plasma object is carried out with the help of a streak-camera.

The dependence of the reflective characteristics of shock-compressed strongly nonideal inert gas plasma on its thermodynamic parameters was studied in the near infrared using a pulsed two-stage yttrium aluminum garnet laser with switching the q-factor of the resonator and higher order mode suppression of laser radiation. To determine the Stokes vector components, a four channel high speed device with filters for selection of probing frequency was used. The device allows to measure the reflected laser beam intensity for four azimuthal angles [8].

New measurements of polarized reflectivity coefficients of explosively driven dense plasmas have been carried out using laser light of the frequency $\nu_{\text{las}} = 2.83 \times 10^{14}$ s$^{-1}$ at incident angles $\theta = 0\text{--}50^\circ$ (for free-electron number density $n_e = 3.3 \times 10^{21}$ cm$^{-3}$) and $\theta = 75\text{--}78^\circ$ (for free-electron number density $n_e = 5.2 \times 10^{21}$ cm$^{-3}$) simultaneously for s- and p-polarization.

3. **Experimental results and analysis**

The results of our measurements and previously obtained data are presented in tables 1 and 2. The composition and thermodynamic parameters of the plasma were determined using the modified Saha IV [10, 11], taking into account the measured velocity of the shock wave in the
Table 1. Experimental data for the s- and p-polarized reflectivities of explosively driven dense xenon plasma at $\nu_{\text{las}} = 2.83 \times 10^{14} \text{ s}^{-1}$, free-electron number density $n_e = 5.2 \times 10^{21} \text{ cm}^{-3}$ and thermodynamic parameter values: pressure $P$, temperature $T$, mass density $\rho$, 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      | 0.25 | 0.25 | 5.3     | 34500 | 1.3            | $5.2 \times 10^{21}$ | $1.3 \times 10^{21}$ | 0.8          | 1.4   | 2.7     |
| 10     | 0.28 |      |         |       |                |                    |                |              |       |         |
| 15     | 0.35 | 0.21 |         |       |                |                    |                |              |       |         |
| 20     | 0.39 | 0.22 |         |       |                |                    |                |              |       |         |
| 25     | 0.4  | 0.17 |         |       |                |                    |                |              |       |         |
| 30     | 0.55 | 0.18 |         |       |                |                    |                |              |       |         |
| 35     | 0.52 | 0.2  |         |       |                |                    |                |              |       |         |
| 40     | 0.58 | 0.13 |         |       |                |                    |                |              |       |         |
| 45     | 0.57 | 0.2  |         |       |                |                    |                |              |       |         |
| 50     | 0.69 | 0.17 |         |       |                |                    |                |              |       |         |
| 55     | 0.67 | 0.27 |         |       |                |                    |                |              |       |         |
| 60     | 0.72 | 0.32 |         |       |                |                    |                |              |       |         |
| 65     | 0.74 | 0.51 |         |       |                |                    |                |              |       |         |
| 70     | 0.85 | 0.58 |         |       |                |                    |                |              |       |         |
| 75     | 0.83 | 0.64 |         |       |                |                    |                |              |       |         |
| 78     | 0.89 | 0.78 |         |       |                |                    |                |              |       |         |

Table 2. Experimental data for the s- and p-polarized reflectivities of explosively driven dense xenon plasma at $\nu_{\text{las}} = 2.83 \times 10^{14} \text{ s}^{-1}$, free-electron number density $n_e = 3.3 \times 10^{21} \text{ cm}^{-3}$ and thermodynamic parameter values: pressure $P$, temperature $T$, mass density $\rho$, 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      | 0.14 | 0.14 | 3.1     | 33200 | 0.83           | $3.3 \times 10^{21}$ | $8.3 \times 10^{20}$ | 0.8          | 1.2   | 3.5     |
| 10     | 0.175|      |         |       |                |                    |                |              |       |         |
| 15     | 0.22 | 0.13 |         |       |                |                    |                |              |       |         |
| 20     | 0.225| 0.1  |         |       |                |                    |                |              |       |         |
| 25     | 0.21 | 0.08 |         |       |                |                    |                |              |       |         |
| 30     | 0.29 | 0.075|         |       |                |                    |                |              |       |         |
| 35     | 0.33 | 0.1  |         |       |                |                    |                |              |       |         |
| 40     | 0.35 | 0.09 |         |       |                |                    |                |              |       |         |
| 45     | 0.44 | 0.073|         |       |                |                    |                |              |       |         |
| 50     | 0.42 | 0.12 |         |       |                |                    |                |              |       |         |

gas, the equations of states of the gas cell material and the gas under study. Tables 1 and 2 also shows the plasma parameters realized in the experiment. Previously [8,9], when calculating the plasma composition, annoying technical errors were made. Table 1 contains corrected data.
Figure 2. S- and p-polarized reflectivity indexes of strongly correlated dense plasma calculated in comparison to the experimental data [6–9] (and this work) for free-electron number density $n_e = 5.2 \times 10^{21} \text{ cm}^{-3}$ and laser light at $\nu_{\text{las}} = 2.83 \times 10^{14} \text{ s}^{-1}$. $L$ is the width of the plasma transition region. The $R_{\text{calc}} L = 0.5 \text{ nm}$ curve and the $R_{\text{calc}} L = 0.5 \text{ nm}$ curve are the calculations with the fixed width of the plasma transition layer.

For comparison with the experiment, the reflectivity of the studied plasma was calculated on the basis of the numerical solution of the field equations. At the same time, the generalized Drude formalism was used to record the dielectric function of the medium. The plasma in question contains highly interacting charged particles, which play a crucial role in such a medium and can be adequately described on the basis of quantum statistical theory. In our work, we calculated the dynamic collision frequency of charged particles, which is included in the expression for the permittivity function, in the Born approximation [12]. In the calculations, we utilized a Fermi-like profile for the density of free electrons in the shock wave front

$$n_{e, \text{Fermi}}(z) = \frac{n_e}{1 + \exp[-z/A - \exp(-z/B) - C]},$$

where $A$, $B$ and $C$ are fit parameters, $n_e$ is the free electron density in the plasma zone from experiment. The influence of neutral particles was taken into account by the frequency of static collision via the neutral contribution coefficient [7].

Figure 2 displays both new experimental data on the reflective properties of strongly nonideal plasma and the data obtained earlier for the laser frequency $\nu_{\text{las}} = 2.83 \times 10^{14} \text{ s}^{-1}$ and the free-electron number density $n_e = 5.2 \times 10^{21} \text{ cm}^{-3}$. Here we show new calculation results for dense plasma optics for the whole set of experimental data in accordance with the approach described above. For comparison, figure 2 shows curves for s- and p-polarization calculated with a fixed width of the transition layer of shock-compressed plasma $L = 0.5 \text{ nm}$. It is clearly seen
Figure 3. S- and p-polarized reflectivity indexes of strongly correlated dense plasma calculated in comparison to the experimental data (this work) for free-electron number density \( n_e = 3.3 \times 10^{21} \text{ cm}^{-3} \) and laser light at \( \nu_{\text{las}} = 2.83 \times 10^{14} \text{ s}^{-1} \). \( L \) is the width of the plasma transition region. The \( R_{\text{calc}}^p L = 0.5 \text{ nm} \) curve and the \( R_{\text{calc}}^s L = 0.5 \text{ nm} \) curve are the calculations with the fixed width of the plasma transition layer.

that calculations with a small front width do not describe the experimental data well, and the resulting Brewster angle differs greatly from the experimental value.

In figure 3, new experimental data and calculation results for the laser frequency \( \nu_{\text{las}} = 2.83 \times 10^{14} \text{ s}^{-1} \) and the free-electron number density \( n_e = 3.3 \times 10^{21} \text{ cm}^{-3} \) are presented. Similarly, in figure 3, one can see the calculation results with the width of the transition layer \( L = 0.5 \text{ nm} \).

As a result of solving the variational problem, the spatial parameters of the plasma transition layer were found. For free-electron number density \( n_e = 5.2 \times 10^{21} \text{ cm}^{-3} \) the width of the transition layer is \( L = 205 \text{ nm} \) (\( A = 0.014, B = 1.12 \) and \( C = 0 \)) and for \( n_e = 3.3 \times 10^{21} \text{ cm}^{-3} \) is \( L = 260 \text{ nm} \) (\( A = 0.017, B = 1.08 \) and \( C = 0 \)).

4. Conclusion

New data and calculation results for reflective characteristics of strongly correlated plasma are presented. Experimental data on the optics of a matter under high-intensity pulsed effect are of great importance for validating theoretical models describing the behavior of the medium at high temperatures and pressures.

Our calculations show that Fresnel approximations or calculations for the near-zero width of the plasma transition layer do not adequately describe the experiment. In contrast, the use of blurring the shock wave front allows us to more accurately describe experiments on studying the reflection from dense plasma. It should be noted that within the framework of the above
approach, it is possible to describe the entire set of experimental data on the optics of strongly correlated plasma.

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