Anomalous Transparency Induced by High Intensity Laser Pulses

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Abstract. Enhanced transmission of laser light through thin films has been studied analytically. It has been supposed that the laser light creates a plasma consisting of successive layers having different optical properties. The transmission properties of the laser light through this media has been given. It has been shown that the transmission coefficient depends on the intensity parameter, on the angle of incidence and on the electron temperature.

The propagation of an intense laser pulse in a plasma layer is of interest for understanding laser plasma interactions and its most important application, the inertial confinement fusion. One of the most interesting phenomena is the transition from opacity to transparency of a plasma layer named anomalous transmission. When an intense laser light hits a thin solid foil high density plasma is formed. If the intensity of the laser light is high enough (near the relativistic threshold) and the duration of the pulse is short (shorter than 1 nanosecond) the transmissivity of the plasma can be approximately 1. Anomalous transmission of laser light through thin slabs of plasma has been observed in several experiments $[1, 2]$. The effect was observed in plasmas produced by relatively long (500 ps [1]) and short (30 fs [2]) laser pulses. Many authors attributed the optical transparency to the strong magnetic field induced by ionization or it has been supposed that this anomalous transparency is the result of mixing of two electromagnetic waves with appropriate frequencies.

In the model, which we intend to present here we have used a simple analytical treatment to calculate the transmission coefficient (the ratio between the amplitude of the transmitted and incident electric field) and transmissivity (the ratio between the intensity of the transmitted and incident light) of plasmas produced by laser pulses. It is important to note, that the thickness of the plasma is a few percent of the wavelength of the laser pulse, and the pulse length is assumed to be shorter than 100 fs.

We assumed that a p-polarized monochromatic electromagnetic plain wave $\vec{E}_{in} = E_{in} \cdot expi[(\omega t - \vec{k}\vec{r})]$ impinges a solid thin foil as can be seen in Fig.[1]. The angle of incidence is denoted by θ_{in}. $\vec{k}$ represents the wave vector, ω the frequency of the laser light. The amplitude E_{out} of the electric field and the direction of propagation (θ_{out}) of the electromagnetic wave at the rear side of the foil is determined as a function of the parameters of the incident laser light.

The laser light ionizes the thin solid foil and a plasma is created as a result of the ionization. It is assumed, that the electron density increases linearly: $n(z) = n_{cr}qz + n_{cr}(1+\ln(p))$, if $n < n_{cr}$ and exponentially: $n(z) = n_{cr}p^{(qz)}$, if $n > n_{cr}$ as seen in Fig. [2a]. n_{cr} represents

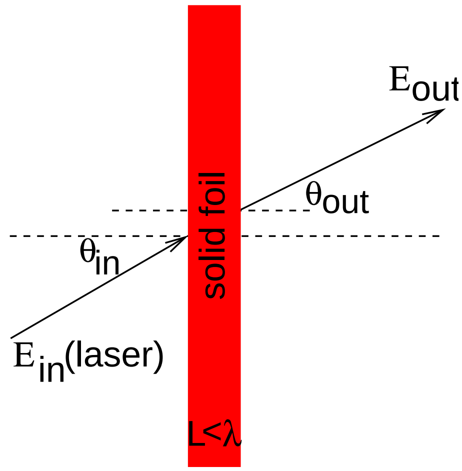


Figure 1: *The interaction of the laser light with the solid foil*

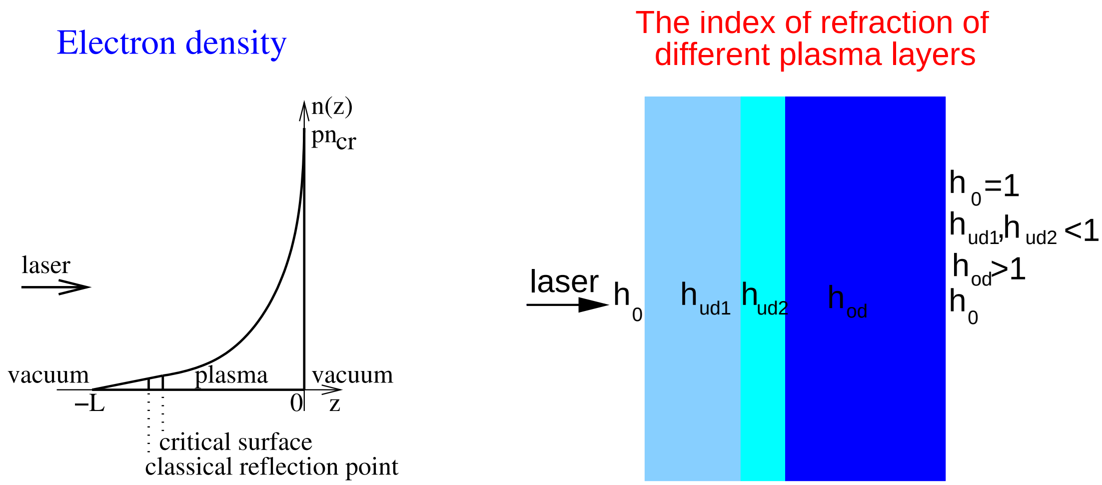
the critical density and is defined as the density where the local plasma frequency equals the laser frequency. The z axis is perpendicular to the surface of the foil. The parameters of the profile are p and q. The ions forms a static background. The dielectric function and the index of refraction of the plasma is defined as a function of the electron density and the electron temperature. The dielectric function is:

$$\epsilon(z) = 1 - \frac{n(z)}{n_{cr}} + i\frac{\nu}{\omega}\frac{n(z)}{n_{cr}}, \tag{1}$$

where $\omega_p^2(z) = 4\pi n(z)e^2/m$ denotes the local plasma frequency and $\nu = 2.91 \cdot 10^{-5} \cdot n(z) \cdot T_e^{-1.5} \cdot Z[1/s]$ denotes the electron-ion collision frequency. Z is the atomic number of the target material and T_e is the electron temperature which has been considered constant. We use the following notations: $c(z) = 1 - \frac{n(z)}{n_{cr}}$ and $d(z) = \frac{\nu}{\omega}\frac{n(z)}{n_{cr}}$. The index of refraction can be given as a function of $c(z)$ and $d(z)$ (see [3]):

$$\eta(z) = \sqrt{\sin^2\theta_{in} + \left[(c(z) - \sin^2\theta_{in})^2 + d(z)^2\right]^{\frac{1}{2}}\cos^2\left(0.5 \cdot \mathrm{arctg}\frac{d(z)}{c(z) - \sin\theta_{in}}\right)}. \tag{2}$$

In the case of plasmas with continuously varying density profile it is worth to distinguish two separate regions from the point of view of the optical density. There is an optically thin, i.e. underdense region (where the electron density is smaller than the critical density) and an optically dense, i.e. overdense region (where the electron density is higher than the critical density). The electromagnetic field penetrates into the underdense plasma to the surface determined by the classical reflection point, which is still in the underdense plasma. This way the underdense region can also be divided into two regions: one region is situated between the vacuum and the classical turning point (denoted by ud1) and the second region is situated between the classical turning point and the critical surface (denoted by ud2). As it was shown [3] in the case of steep density profiles the distance between the classical turning point and the critical surface can be only a few per cent of the wavelength of the laser light and the index of refraction of the layers bounding the layer denoted ud2 is higher than the index of refraction of this layer. (In Fig. [2b] are shown the the consecutive layers having different optical densities. The optical properties are characterized by the



(a) The dependence of electron density profile normalized to th the critical density on the normalized coordinate z/λ.

(b) The index of refraction corresponding to the electron density profile sketched on the right side.

Figure 2: *The interaction of the laser light with the solid foil*

index of refraction η_{ud1}, η_{ud2} and η_{od}, where the index denotes the layer. $\eta_0 = 1$ is the index of refraction of the vacuum.) This way the electromagnetic wave does not totally reflect and frustrated internal total reflection takes place. The phenomenon, that the light could penetrate into an optically rare medium from an optically dense medium even if the angle of incidence is larger than the Brewster angle is named frustreted total internal reflection. The effect is more interesting if behind the optically rare media is situated an optically dense media, as it is in our case. As a consequence of frustrated internal total reflection the wave can penetrate in the overdense region as an inhomogeneous electromagnetic wave. It is known that the amplitude of the electric field is enhanced near the surface determined by the classical reflection point. The thickness of the layer ud2 is very small the amplitude of the electromagnetic field penetrates in the overdense region without decay.

The direction of propagation of the laser light at the rear of the foil can be given directly by the Snell-Descartes formulae because $\eta_0 \sin\theta_{in} = \eta_0 \sin\theta_{out}$, where $\eta_0 = 1$ is the index of refraction of the vacuum. This way $\theta_{out} = \theta_{in}$, so the direction of propagation at the backside of the foil will be the same as the direction of propagation of the incident laser light.

The transmission of the laser light through the plasma was calculated summing up the changes of the amplitude of the electric field at the interface of the different plasma layers. The amplitude of the electric field changes when the light penetrates from the vacuum in the layer ud1. The transmission coefficient can be given by the Fresnel formulae:

$$t_{0,ud1} = \frac{2}{\frac{\epsilon_{ud1}}{\epsilon_0} + \sqrt{\frac{\epsilon_{ud1} - \epsilon_0 \sin^2\theta_{in}}{\epsilon_{ud1}(1 - \sin^2\theta_{in})}}}. \quad (3)$$

The thickness of this layer is very small, so we will neglect the decay of the wave during its propagation in this media.

Because of frustrated total internal reflection in the layer ud2 we don't know exactly how propagates the laser in this media. We calculated the transmission of the wave through this layer as an infinitesimal layer. The transmission coefficient of this thin layer is given by:

$$t = \frac{1 + t_{ud1,ud2} t_{ud2,od} exp(i\delta)}{1 - r_{ud1,ud2} r_{ud2,od} exp(2i\delta)}, \tag{4}$$

where $\delta = \frac{2\pi}{\lambda} dz \sqrt{\eta_{ud2}^2 - \eta_{ud1}^2}$. The transmission coefficients has analogous form with $t_{0,ud1}$ and the reflection coefficients has has analogous form with: $r_{ud1,ud2} = \left(1 - \frac{\epsilon_{ud1}}{\epsilon_{ud2}} \sqrt{\frac{\epsilon_{ud2} - \epsilon_{ud1} \sin^2 \theta_{in}}{\epsilon_{2ud}(1 - \sin^2 \theta_{in})}}\right) \Big/ \left(1 + \frac{\epsilon_{ud1}}{\epsilon_{ud2}} \sqrt{\frac{\epsilon_{ud2} - \epsilon_{ud1} \sin^2 \theta_{in}}{\epsilon_{ud2}(1 - \sin^2 \theta_{in})}}\right)$.

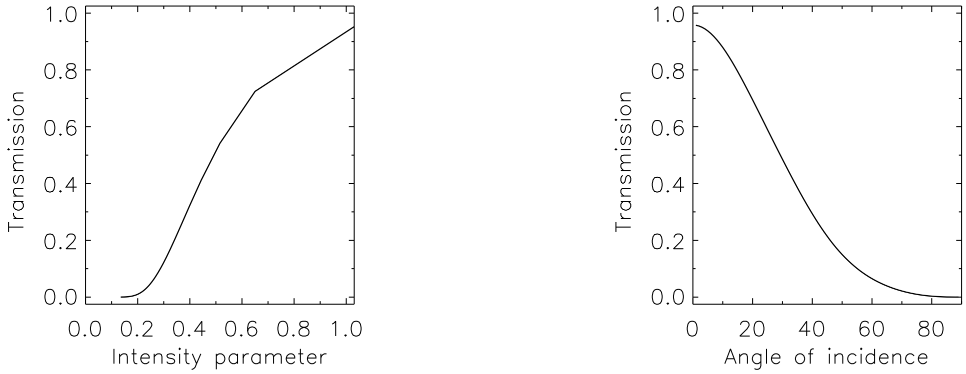
The overdense region is a relatively thick layer so the decay of the electric field cannot be neglected as in the ud1 region. The decay can be taken into account by the use of the following equation [3]:

$$E^{od}(z) = \frac{\cos^{\frac{1}{2}} \theta_0}{((c(z) - \sin\theta_0)^2 + d(z)^2)^{\frac{1}{8}}} \\ exp\left[-\frac{\omega}{c}((c(z) - \sin\theta_0)^2 + d(z)^2)^{\frac{1}{4}} \cdot \sin\left(\frac{1}{2}\text{arctg}\left(\frac{d(z)}{c(z) - \sin\theta_0}\right)\right) z\right] E_0. \tag{5}$$

After the wave passes the overdense region it enters again the vacuum. The transmission coefficient is analogous with $t_{0,ud1}$. Squering the transmission coefficient can be obtained the transmissivity. Summing up the changes of the amplitude of the electric field the transmission coefficient of the plasma can be given as a function of the parameters of the density profile. The parameter p of the density profile is related to the intensity parameter $\mu = 10^{-9}\sqrt{I}[W/cm^2]\lambda[\mu m]$ (I denotes the intensity of the incident laser light and λ is the wavelength of the laser light) by the use of the Keldish formulae $p = const1 \cdot \exp\left(-\frac{const2}{\mu}\right)$. To obtain a realistic density profile the following relations must be fullfilled: $L_{pl} < 0.5\lambda$ and $\int_0^{L_{pl}} n(z)dz = L_{foil} * n_{foil}$, where L_{foil} is the thickness of the foil and n_{foil} is the electron density of the foil. According to this considerations $const1 = 1.4 \cdot 10^4$, $const2 = -5.9$ and q=10 has been choosen.

We obtained the transmission coefficient and transmissivity of the plasma as a function of different parameters. The transmissivity increases as the intensity parameter increases. It can be seen, that the transmissivity is approximately 1, if the intensity parameter reaches 1. The dependence of the transmissivity on the intensity parameter can be seen on Fig. [3a]. The calculations has been made for the same parameters which has been used in the experimental work presented by Giuletti et al. in [2]. These parameters are the wavelength of the incident laser light $\lambda = 785nm$, angle of incidence $\theta_{in} = 45°$, the scale length of the plasma $l \sim 0.2\lambda$, electron temperature $T_e = 300eV$. A good correspondence has been found between the experimental data and the theoretical results.

We calculated the dependence of the transmissivity on the angle of incidence of the laser beam. The transition from opacity to transparency is much more pronounced if the



(a) The dependence of the transmissivity on the intensity parameter. The graphic has been made by the use of the following parameters: the wavelength of the incident laser light $\lambda = 785nm$, angle of incidence $\theta_{in} = 45°$, the scale length of the plasma $l \sim 0.2\lambda$, electron temperature $T_e = 300eV$.

(b) The dependence of the transmissivity on the angle of incidence. The graphic has been made by the use of the following parameters: the wavelength of the incident laser light $\lambda = 785nm$, the intensity parameter $\mu = 0.86$, the scale length of the plasma $l \sim 0.2\lambda$, electron temperature $T_e = 300eV$.

Figure 3: *The transmissivity as a function of the intensity parameter (a) and as a function of the angle of incidence (b).*

angle of incidence is lower than 45°, because in this case the condition for frustrated total reflection are more favorable. The dependence of the transmissivity on the angle of incidence can be seen in Fig. [3b].

The electron-ion collision frequency and the index of refraction depends on the electron temperature. We also have obtained that the temperature of the electrons influence the transmissivity. We have found that the dependence of the transmissivity on the electron temperature is much weaker than the dependence on the intensity parameter and on the angle of incidence. That is the reason why the rough approximation of constant temperature could be taken. Calculations with realistic plasma models are in progress.

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References

[1] FUCHS, J. et al., "Transmission through Highly Overdense Plasma Slabs with Subpicosecond Relativistic Laser Pulse", Phys. Rev. Lett. **80** (1998) 2326.

[2] GIULIETTI, Daniele et al., "Observation of Solid Density Laminar Plasma Transparency to Intense 30 Femtosecond Laser Pulses ", Phys. Rev. Lett. **79** (1997) 3194.

[3] GÁL, Kinga and VARRÓ, Sándor, "Polarization Properties of High Harmonics Generated on Solid Surfaces", Opt. Commun. **198**, (2001) 419.