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Research on breakdown threshold and directivity of sound field generated by ultrashort laser pulses induced liquid breakdown

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ABSTRACT

By using experimental results and taking into account the characteristics of shaping in the focal region, we theoretically demonstrate the plasma ellipsoid model and calculate the breakdown threshold and the directivity of the sound filed. It is found that the predictions in our theoretical model well agree with the results of experiments.
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1. Introduction

The interaction between a high power laser pulse and a liquid material can excite sound waves, and this process is often referred to a laser-acoustic source [1–3]. When the laser energy density is more than the liquid medium breakdown threshold, optical breakdown is the main mechanism. Optical breakdown by ultrashort laser pulses has grown rapidly in the past few years. Compared with long-pulse lasers, ultrafast breakdown can be more readily controlled by modulating the irradiated laser intensity. Accordingly, it has great interest in medical and biological applications especially in remote sensing technology in the underwater acoustics [3–5]. It is of great importance to study the breakdown threshold and the directivity of the sound filed, for such practical applications as selection of optical breakdown conditions and design of the signal reception system in ocean exploration.

Research on the breakdown threshold and the directivity of the sound filed in liquids induced by laser pulses has been reported [1,6–12]. To date, the works have been developed based on the focal volume of the cylindrical volume. However, the experimental results [13–15] show that the shape of the focal region for optical breakdown in liquids is similar to an ellipsoid rather than a cylinder. In this work, we put forward a three-dimensional model named plasma ellipsoid model. The breakdown threshold and the directivity of the sound filed are calculated using the plasma ellipsoid model, and then the directivity patterns of sound field are mapped and analyzed through numerical simulation. The results of experiment fit the theory well.

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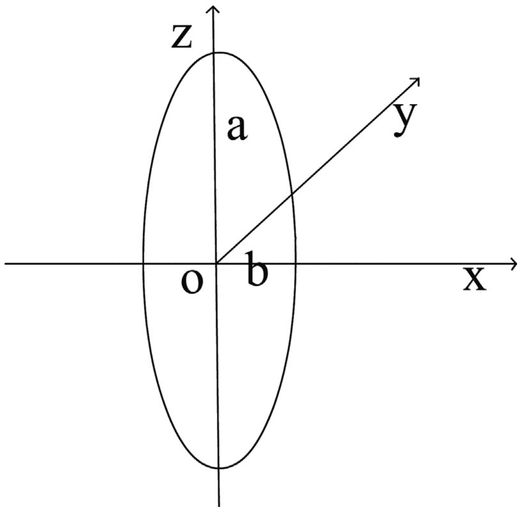

Fig. 1. Plasma ellipsoidal model.

2. Plasma ellipsoidal model

For ultrashort laser pulses, the laser beam is focused to a small spot to increase the intensity above the breakdown threshold. The focal volume is assumed to be ellipsoidal. The plasma ellipsoid model is established combining the shape of the irradiance and free-electron density distributions within the focal volume, as shown in Fig. 1. The *z*-axis is the direction of the incident laser pulse. The semi-major axis *a* and semi-minor axis *b* of the ellipsoid are related to the laser energy and the laser illumination zone.

In the focal volume, the incoming laser power is both time and position dependent. We approximate the ellipsoidal region of high irradiance in the focus by a Gaussian function. Thus, the laser intensity takes the form

$$I(t,x,y,z) = I(0,0,0,0)\exp\left[-2\left(\frac{x^2+y^2}{b^2}+\frac{z^2}{a^2}\right)\right]\exp\left[-4\ln 2\left(\frac{t}{t_p}\right)^2\right]. \tag{1}$$

In Eq. (1), $I(0, 0, 0, 0)$ is the peak of the pulse irradiance. Note that $x=0$, $y=0$, $z=0$ represent the beam focus, and $t=0$ corresponds to the pulse peak $I(0, 0, 0, 0)$ arriving at the focal region. t_p is the full width at half maximum pulse duration. The boundaries of the ellipsoid correspond to the $1/e^2$ values of the Gaussian irradiance distribution.

3. Breakdown threshold

3.1. Electron diffusion and recombination

When the liquid medium in the focal region of a high-power laser pulse is ionized and free electrons are formed in the focal volume, two processes will reduce the electron population: diffusion and recombination. If the decrease of the electron density in the focal volume by electron diffusion is estimated, we can approximate the focal volume by the plasma ellipsoid model.

The loss rate is the rate of diffusion out of the focal volume, given by [8]

$$\eta_{\text{diff}} = \frac{\tau \Delta E}{3 m_e \Lambda^2}. \tag{2}$$

In Eq. (2), the liquid is treated as an amorphous semiconductor with a band gap ΔE, which is also treated by others [6]. τ is the mean free time between collisions, m_e is the rest mass of an electron and Λ is the characteristic diffusion length.

The characteristic diffusion length is related to the geometrical shape of focal volume. Thus, Λ the characteristic diffusion length of the breakdown region, is defined as

$$\Lambda = B_g^{-1}, \tag{3}$$

where B_g is the geometric buckling of the ellipsoid. It should be noted that the geometric size effect is considered as the main effect on the electron diffusion.

In the stationary state, B_g is the smallest eigenvalue of the wave equation Eq. (4) at boundary condition of Eq. (5) [16]

$$\nabla^2\phi + B_g^2\phi = 0, \tag{4}$$

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