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Modeling of laser heating GaAs considering the effects of atmospheric thermal blooming with crosswind

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ABSTRACT

In this paper, a two-dimensional (2-D) modeling for temperature of GaAs irradiated by laser considering the effects of atmospheric thermal blooming with crosswind is presented. By using analytical expression of distorted laser intensity for the atmosphere thermal blooming with crosswind, the theoretical 2-D plane heat transfer model of laser irradiating GaAs after the action of atmosphere thermal blooming is established. Integral transform method is used to solve the heat transfer equation and its analytical solutions are obtained. The effects of thermal blooming on temperature distributions of GaAs are studied. Results show that the crosswind and the laser propagation distance have obvious influences on the thermal blooming, thereby affecting the temperature distributions of GaAs induced by distorted laser. The smaller the crosswind velocity is, the stronger the thermal blooming is, which leads to a higher distortion of temperature distributions. On the other hand, the farther the laser propagation distance in atmosphere is, the stronger the thermal blooming is, which also leads to the higher distortion of temperature distributions.

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1. Introduction

Modeling of laser heating is very important for laser applications such as laser processing and laser damage, because it can not only reduce the experimental cost and time, but also can provide results under many conditions including the extreme conditions that the experimentation is difficult to achieve. Moreover, analytical modeling has always been very attractive to researchers because it can establish an intuitive relationship between parameters and results, which has important significance to reveal the physical mechanism of laser-matter interaction and optimize the laser or workpiece parameters [1–8].

In the current studies of laser heating, most of laser beams are assumed to irradiate onto material surface directly without any medium. But in the potential applications of laser in the fields such as industry or military, it often encounters that the laser propagates in the atmosphere, and then irradiates onto the material surface. Laser propagation in the atmosphere is a very complicated physical process, especially the thermal blooming induced by laser heating air. When the laser propagates in the atmosphere, the nonlinear effects will cause the distortion of the laser beam, which will lead to the thermal blooming [9–15]. Thermal blooming can affect the quality of the laser beam, which leads to the instability of the laser propagation,

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and affects the interaction between the laser and material. Thermal blooming is very important for the study of intense laser propagation in the atmosphere, which dominates laser distortion due to atmosphere.

After the effects of the atmospheric thermal blooming, the laser intensity distribution on the material surface is no longer regular. At this time, it needs to solve a 2-D or 3-D heat transfer problem when the irregular laser heating material is modeled. In this paper, we present 2-D plane modeling for distorted laser heating material considering the atmospheric thermal blooming with crosswind and investigate the effects of thermal blooming on the heat transfer in the material.

GaAs is widely used in the optoelectronic devices because of its wide band gap and direct band gap. When the optoelectronic devices work under the intense laser environment, they often face performance degradation and failure even induced damage due to laser heating. It is important to study the interaction of laser with GaAs and its heating mechanisms for destruction and protection of the optoelectronic devices. So we present a 2-D modeling of laser heating GaAs considering the effects of atmospheric thermal blooming in this paper. It is organized as follows. In Section 2 we introduce the theoretical models of thermal blooming and distorted laser heating GaAs, and analytical solutions of the temperature distributions induced by a thermal blooming laser heating are obtained. Results of thermal blooming and temperature for different crosswind and propagation distance are presented in Section 3. Our main conclusions are summarized in Section 4. It is pointed out that, in this paper, a collimated continuous wave (CW) laser is considered, and the thermal blooming is assumed to be steady state.

2. Mathematical modeling

2.1. Thermal blooming modeling

We assume that d is the laser propagation distance in the atmosphere and x,y are the variables in transverse plane. From reference [9,10], the scalar wave equation in parabolic approximation is,

$$\nabla_T^2\psi + 2ik_0\frac{\partial\psi}{\partial z} + k_0^2\left[\frac{n^2(x,y,d,t)}{n_0^2} - 1\right]\psi = 0 \tag{1}$$

where, n is refractive index of atmosphere, n_0 is static refractive index, k_0 is wave number, ψ is the field amplitude and $\nabla_T^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$.

The structural equation can be written as:

$$\frac{n^2}{n_0^2} - 1 \approx 2\left(n_0 - 1\right)\frac{\rho_1}{\rho_0} \tag{2}$$

where, ρ_0 is the density of the atmosphere with no distorting, and ρ_1 is the change of the density of atmosphere and yields,

$$\frac{\partial\rho_1}{\partial t} = \frac{1-\gamma}{c_s^2}\alpha I_p \tag{3}$$

where, $\gamma = \frac{c_p}{c_v}$, c_p and c_v is specific heat capacity at constant pressure and constant volume respectively, $c_s^2 = \sqrt{\gamma\frac{\partial p}{\partial\rho}}$ is the sound velocity, p is the atmospheric pressure, and ρ_p is the density of atmosphere.

When the laser is a collimated beam, the diffraction effect can be neglected due to the large Rayleigh distance. Form the reference [16], in the steady state, the expression of the thermal blooming laser intensity can be written as:

$$I_p(x,y,d) = I_0 e^{-\mu d}\exp\left[-\left(x^2+y^2\right)/r_0^2\right]\exp\left[-N_C\phi_0(x,y)g_1(\mu d)\right] \tag{4}$$

where, μ is the laser absorption in atmosphere, r_0 is the waist radius of Gaussian beam, and N_c, $\phi_0(x,y)$, $g_1(\mu d)$ yield:

$$N_C = -\mu\frac{dn}{dT}\frac{d^2 I_0}{\rho c_p v_x r_0} \tag{5}$$

$$\phi_0(x,y) = \frac{2x}{r_0}\exp\left[-\left(x^2+y^2\right)/r_0^2\right] + \left(1 - \frac{4y^2}{r_0^2}\right)\frac{\sqrt{\pi}}{2}e^{-\frac{y^2}{r_0^2}}\left[1 + \mathrm{erf}\left(\frac{x}{r_0}\right)\right] \tag{6}$$

$$g_1(\mu d) = \frac{2}{\mu d}\left(1 - \frac{1-e^{-\mu d}}{\mu d}\right) \tag{7}$$

where, v_x is the crosswind velocity along the x direction, N_C is the distortion parameter, and $\frac{dn}{dT}$ is the temperature change ratio of the refractive index of the atmosphere. The distortion parameter N_C is the key parameter to describe the intensity of thermal blooming, we will discuss the effect of distortion parameter on thermal blooming in the third part of this paper.

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