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The damage of the optical components induced by the stimulated Brillouin scattering*

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A theory of excitation of ultrasonic waves in the stimulated Brillouin scattering (SBS) process is presented in this paper. By using several reasonable approximations, a numerical calculation of the transient longitudinal SBS shows that large amplitude of acoustic waves can be built up by the nanosecond pulse of high-power laser, which may result in the damage of optical glasses. The maximal density change and the maximal acoustic wave intensity in optical glasses of 5 cm in thickness are calculated by using different parameters of the high-energy laser, such as the intensity, the pulse width, and the wave length. The damage threshold of the optical glasses is about 80 GW/cm^2 when using a 1064 nm laser. The dynamic mechanism of SBS is the electrostriction effect of the components coupling with the high-power laser.

Keywords: transient longitudinal SBS, damage of the optical glasses, ultrasound wave, intensity of acoustic wave

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1. Introduction

In a high-power laser system, such as laser fusion drivers, the high-energy laser can lead to the damage of components in a glass device and to energy losses.[1−3] Stimulated Brillouin scattering (SBS) is one of the allowed nonlinear process in all media. The SBS in optical materials is important in a number of laser applications because SBS removes energy from the transmitted waves to the stimulated scattering waves and simultaneously generates an intense acoustic wave that could fracture windows. The dynamic mechanism of SBS is the electrostrictive effect of the nanosecond pulse laser. So with a short-pulse ($<$ 10nsec) and narrow-band ($<$0.5 cm^{-1}) of high-power laser, the laser creates the potential for producing transient longitudinal SBS process,[4−6] which has previously been associated with the damage in mirrors and windows.[7−10]

Brillouin scattering is the scattering of light by acoustic (density or elastic) waves. Two optical fields form a travelling standing-wave pattern which is a compressional acoustic wave creating an index grating that scatters energy from one optical wave to the other.[11−13] Density variations modulate the index of refraction, and the varying index of refraction scatters Stokes light spatially. This paper studies the pressure of the excitation of ultrasonic waves induced by the SBS process in components in glasses.[14]

2. Theory

The SBS process is a three-wave mixing process involving two optical waves and an acoustic wave in the SBS medium. An acoustic wave field, a pump and a Stokes electric fields are defined by the slowly varying amplitude envelopes through the following relations:

$$\rho(z,t) = \rho_0 + \frac{1}{2}\{Q(z,t)\exp[-\mathrm{i}(\Omega_\mathrm{a}t - q_\mathrm{a}z)] + \mathrm{c.c.}\}, \quad (1)$$

$$E_\mathrm{p}(z,t) = \frac{1}{2}\{P(z,t)\exp[-\mathrm{i}(\omega_\mathrm{p}t - k_\mathrm{p}z)] + \mathrm{c.c.}\}, \quad (2)$$

$$E_\mathrm{s}(z,t) = \frac{1}{2}\{S(z,t)\exp[-\mathrm{i}(\omega_\mathrm{s}t - k_\mathrm{s}z)] + \mathrm{c.c.}\}, \quad (3)$$

where $\rho(z,t)$, $P(z,t)$ and $S(z,t)$ are amplitudes of the sound wave, the pump and the Stokes waves; Ω_a, ω_p

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and ω_s are the frequencies of the acoustic, pump and Stokes waves respectively. q_a, k_p and k_s are the wave vectors of the acoustic, pump and Stokes waves, respectively. In all nonlinear mixing processes, energy and momentum must be conserved:

$$\omega_p = \omega_s + \Omega_a, \quad k_p = k_s + q_a, \tag{4}$$

$$\Omega_a = \frac{2nv_a\omega_p}{c}\sin\left(\frac{\theta}{2}\right). \tag{5}$$

Here θ is the angle between the pump and Stokes wave vectors. v_a is the velocity of the sound wave in the SBS medium; n is the optical index of refraction in the SBS medium and c is the speed of light. The longitudinal SBS geometry is depicted in Fig.1.

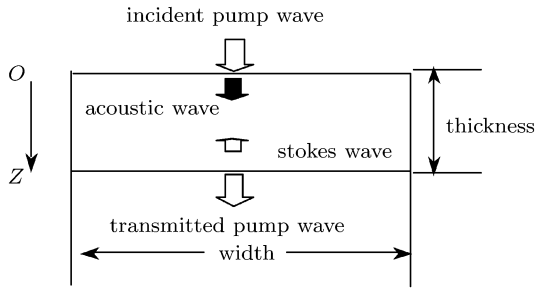


Fig.1. Longitudinal SBS geometry.

For the acoustic field, pump and Stokes fields, the equations solved are

$$\left(\frac{\partial}{\partial t} + \Gamma\right) Q(z,t) = \frac{\mathrm{i}q_a\gamma^e}{16\pi v_a} P(z,t)S^*(z,t), \tag{6}$$

$$\left(\frac{n_p}{c}\frac{\partial}{\partial t} - \frac{\partial}{\partial z} + \frac{\alpha_p}{2}\right) P(z,t) = \frac{\mathrm{i}k_p\gamma^e}{4n_p^2\rho_0} Q(z,t)S(z,t), \tag{7}$$

$$\left(\frac{n_s}{c}\frac{\partial}{\partial t} + \frac{\partial}{\partial z} + \frac{\alpha_s}{2}\right) S(z,t) = \frac{\mathrm{i}k_s\gamma^e}{4n_s^2\rho_0} Q^*(z,t)P(z,t), \tag{8}$$

where Γ is the spontaneous Brillouin linewidth; ρ_0 is the density of the optical glasses; γ^e is the electrostrictive constant $\rho\partial\varepsilon/\partial\rho$. By directly integrating Eqs.(6) and then substituting the results into Eqs.(7) and (8), we obtain two coupled equations. These equations are identical to those for liquids and sufficiently dense gases. α_p and α_s are the background losses of the pump and Stokes intensities per unit time respectively, which are usually small and in the range 10^{-2}–$10^{-3}\,\mathrm{cm}^{-1}$ for optical glasses; $\rho(z,t)$ is proportional to the complex amplitude of the acoustic wave.

From the conservation of mass, we have

$$\nabla(\rho(z,t)V) = 0, \quad u_{zz} = -\frac{d\rho(z,t)}{\rho_0(z,t)}. \tag{9}$$

$$|\Delta\rho|_{\max} = |Q|_{\max} = \left|\frac{\mathrm{i}q_a\gamma^e\varepsilon_0}{16\pi v_a}\int_0^t P(z,t)S^*(z,t)\exp[-\Gamma(t-\tau)]\mathrm{d}\tau\right|_{\max}. \tag{10}$$

The relation among the stress, strain and elastic constants is $\sigma = Yu$. The pressure of the ultrasonic wave P_a is identical to the stress σ. The maximal pressure and intensity of the ultrasonic wave are

$$(I_a)_{\max} = \frac{p_z^2}{2\rho_0(z,t)v_a} = \frac{Y^2}{2\rho_0(z,t)v_a}\left(\frac{\mathrm{d}\rho(z,t)}{\rho_0(z,t)}\right)^2_{\max}. \tag{11}$$

We make the following approximations in this paper. 1) The pump light has a Gaussian profile which is reasonable for high-power laser systems. 2) The optical materials are isotropic. 3) The directions of polarization of the pump and scattered light waves are parallel to each other, this direction being the optimized direction of an amplifier in the transient longitudinal SBS process. 4) Slow-variation envelope amplitude approximation (SVEA) and plane wave approximation are used.

3. Results and discussion

In this paper, we choose a piece of optical glass with a thickness of 5 cm as our sample. In this case,[15] $v_a \approx 5\times10^3\mathrm{m/s}$, $\rho_0 \approx 2.5\times10^3\mathrm{kg/m}^3$, $Y \approx 6.25\times10^{10}\mathrm{Nm}^{-2}$, $q_a \approx 4\pi\times10^6\mathrm{m}^{-1}$, n=1.5132, $\Omega_a \approx 2\pi\times10^{10}\mathrm{s}^{-1}$, and for these constants the damping distance of hypersonic phonons will be about 20μm, i.e. $\alpha_a \approx 5\times10^4\mathrm{m}^{-1}$. Using the Lorentz–Lorenze law $\gamma^e \approx (n^2\text{-}1)(n^2\text{+}2)/3$, $\gamma^e \approx$1.84 can be obtained gen-

erally. Figures 2 and 3 shows the dependences of the ultrasonic wave intensity I_a and the density change $\Delta\rho$ of the glass components induced by the SBS process upon the intensity of the laser light. The density changes $\Delta\rho$ versus the thickness Z of the optical components are depicted in Fig.2. It can be seen that the intensity of the ultrasonic wave grows with increasing thickness in a quasi-exponential way. The thicker the optical component, the higher the ultrasonic wave pressures in the component. If the strain of the medium is about 10^{-3} or the pressure of the ultrasonic wave is about 10^8Pa, it results in the damage of mirrors and windows in the high-power laser system. The output face of the component is first damaged not only by the intensity and pressure on it, but also by the reflection of ultrasonic wave momentum or the impulse on the output face. Therefore, this pressure may damage the output face of the components in a short time and the thresholds of damage of components become lower. The maximal ultrasonic wave intensity $(I_a)_{max}$ and maximal glass material density change $(\Delta\rho)_{max}$ at the output face of the optical components against different pump light power density I_P(GW/cm^2) are

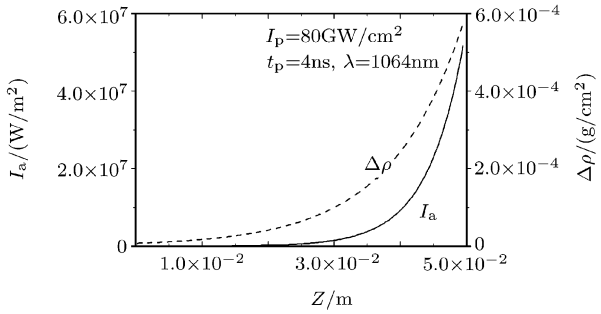


Fig.2. Dependence of the ultrasonic wave intensity I_a and glass material density change $\Delta\rho$ upon the thickness Z of the optical components. τ=4ns, γ^e =1.84, n=1.5132.

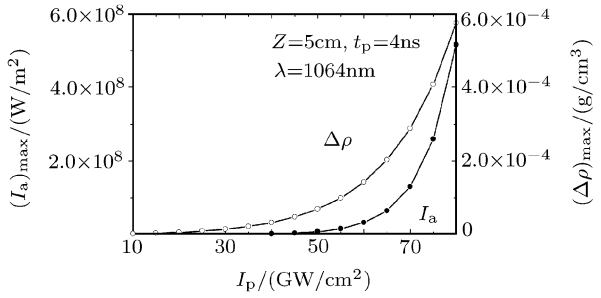


Fig.3. Dependence of the maximal ultrasonic wave intensity $(I_a)_{max}$ and maximal glass material density change $(\Delta\rho)_{max}$ in the optical components upon the power of the pump light I_p. τ=4ns, γ^e =1.84, n=1.5132.

depicted in Fig.3. It is indicated that the acoustic wave intensity I_a in the optical components depends sensitively upon the power density of the pump light. The damage threshold of the optical glasses on using the 1064nm laser is about 80GW/cm^2. It must be considered in a number of laser applications, especially in the high-power laser system.

Figures 4 and 5 show the dependences of the ultrasonic wave intensity I_a and the density change $\Delta\rho$ of the glass material upon the pulse width of the laser light. With the nanosecond pulse laser, the SBS process is easily build up and the effective gain of the SBS is remarkable when the power density of laser is about 80GW/cm^2. The interactions of the high-power laser with the components are also related to the pulse width. The influence of the nanosecond pulse on the components damage is smaller than that of the wavelength and power density of the high-power laser. This process is also affected by the lifetime of the phonons in the transient SBS processes.

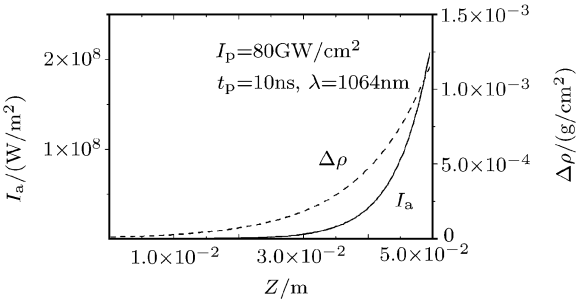


Fig.4. Dependence of the ultrasonic wave intensity I_a and glass material density change $\Delta\rho$ upon the thickness Z of the optical components. τ=4ns, γ^e =1.84, n=1.5132.

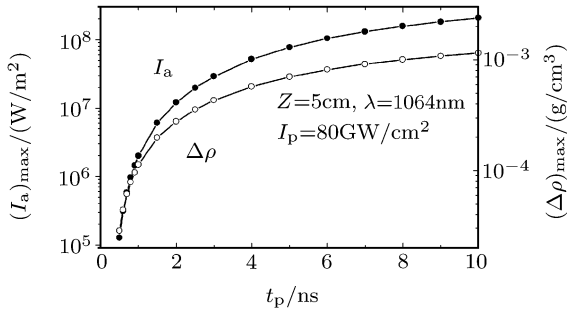


Fig.5. Dependence of the maximal ultrasonic wave intensity $(I_a)_{max}$ and maximal glass material density change $(\Delta\rho)_{max}$ in the optical components upon the pulse width of the pump light t_p. τ=4ns, γ^e =1.84, n=1.513.

We have also studied the relationship between the ultrasonic wave and the wavelength of the high-power laser in the transient SBS. The dependence of

the intensity I_a and glass material density change $\Delta\rho$ upon the wavelength of the high-power laser is shown in Figs.6 and 7. It is indicated that the maximal ultrasonic wave intensity $(I_a)_{max}$ and the maximal glass material density $(\Delta\rho)_{max}$ have changed sensitively with the variation of wavelength of the laser. The pressure in the optical components in SBS processes comes from the electrostrictive effects. From Eqs.(6)–(8), we can see that the coupling coefficient

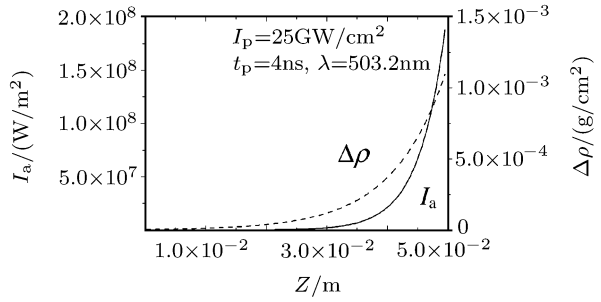


Fig.6. Dependence of the ultrasonic wave intensity I_a and glass material density change $\Delta\rho$ upon the thickness Z of the optical components. τ=4ns, γ^e =1.84, n=1.5132.

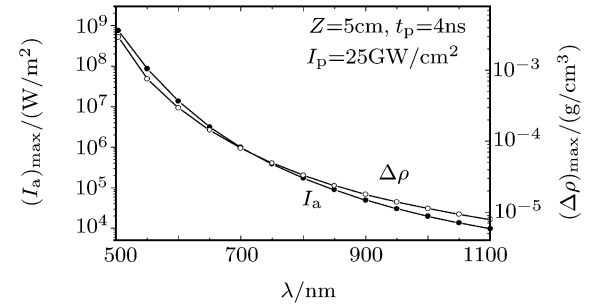


Fig.7. Dependence of the maximal ultrasonic wave intensity $(I_a)_{max}$ and maximal glass material density change $(\Delta\rho)_{max}$ in the optical components upon the wave length of the pump light λ. τ=4ns, γ^e =1.84, n=1.5132.

between optical components (γ^e) and pump light is proportional to the square of the wave vector of the laser. So the transient gain parameter is inversely proportional to the square of the optical wavelength. The transient SBS is most important for the short wavelength of the laser, and the thresholds of the damage of components has been lowered quickly.[16]

According to the theoretical calculation, the following conclusions can be drawn.

(i) The damage thresholds of the component vary with the different parameters of the transmitted laser. The intensity of the ultrasonic waves grows with increasing thickness in a quasi-exponent way. The direct absorption for transparent components is very small, e.g. about 10^{-3}cm^{-1}, which cannot result in direct thermal damage. For the optical glasses, the threshold of the damage due to the nanosecond pulse of the high-power laser is about 80GW/cm^2.

(ii) For 1064nm laser of intensity 80GW/cm^2 with 4 nanosecond pulse, light pressure is about 10^7Pa or bigger, which approaches the strain limit of a rigid body. For a 503.2nm laser, the threshold of the damage is about 30GW/cm^2.

(iii) Two methods that potentially reduce the damage of the component by the SBS are to increase the wavelength of the high-power laser and increase the linewidth to a value much greater than the Brillouin linewidth. However, it will weaken the intensity of ultrasonic waves in a SBS process.

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