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Investigation of stimulated Brillouin scattering for broadband KrF laser*

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Stimulated Brillouin scattering (SBS) numerical mode for broadband multimode KrF laser pump with optical breakdown has been built up in this paper. The basic premises of the model are that KrF spectrum is composed of a number of lines and SBS arises from these lines with coupling to some extent. The broadband SBS threshold strongly depends on pump bandwidth. SBS and optical breakdown occur nearly simultaneously when broadband SBS and breakdown have the same threshold. The decrease of saturation reflectivity for broadband pump radiation is explained with this model. Experimental results agree well with the model.

Keywords: KrF laser, stimulated Brillouin scattering, reflectivity, pulse compression
PACC: 4265C, 4265F

1. Introduction

It is well known that stimulated Brillouin scattering (SBS) can produce phase conjugate reflections of laser radiation.[1] Many theoretical and experimental works[2−9] have been published, which discuss the conditions to achieve stability, high fidelity of conjugate and Brillouin amplification. The majority of this modelling of the SBS phase conjugate mirrors assumes infinitely narrow laser and scattered linewidths. However, in many excimer laser applications, such as laser–target experiments, the use of broadband laser radiation helps suppress deleterious parametric instabilities.[10] Then, it is interesting to investigate the extent to which SBS mirrors are still effective for compensating phase distortions of broadband laser radiation in optically distorted amplifiers.

Many applications of SBS involve the use of broadband laser sources and considerable theoretical and experimental works[11−14] have been performed in the last twenty years to investigate the effect of laser bandwidth on SBS threshold and reflectivity and on optical-phase-conjugation fidelity. At present, there are different results on the problem whether laser lines or laser modes produce SBS independently. Experiments with a two-line XeF laser[15] operating at 351 and 353nm showed that, when the lines were spontaneously separated in the SBS medium (n-hexane), good conjugation and equal reflectivity were seen on both lines. However, when both lines were directed into the same volume, the four-times-stronger 351nm line dropped by a factor 100 with weaker and inconsistent conjugation. The reflectivity of SBS mirrors versus pump intensities at different pump bandwidths $\Delta\nu_{\rm p}$ of the XeCl laser radiation was recently investigated in Ref.[16] by Filippo. It was found with methanol as an active medium that by increasing $\Delta\nu_{\rm p}$ from 37 to 75GHz the threshold intensity for SBS remained unchanged and the reflectivity was strongly dependent on $\Delta\nu_{\rm p}$. It was found later that the Brillouin mirror performance could be improved by setting a disperse element in front of the mirror and both lines of the XeCl spectrum did not drive SBS independently.[17] SBS of pulsed multiline hydrogen fluoride laser radiation has been investigated in

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Ref.[18]. It was found that the individual lines were scattered independently, and experiments comparing SBS efficiency with phase-conjugate fidelity for common and spectrally dispersed focal volumes produced similar results.

It has been known that broadband SBS saturation reflectivity is decreased.[19] And it has been found for a decreased reflectivity at higher pump intensities.[16] This is due to competition between SBS and other nonlinear processes such as stimulated Raman scattering and self-focusing. But this was not explained clearly in Ref.[16].

In this paper a KrF laser system is used to investigate the reflectivity versus pump energy for a broadband pump. A broadband SBS numerical mode is developed for a multimode KrF pump laser with optical breakdown.

2. Broadband SBS model and numerical calculation

2.1. Broadband SBS model

In this section, we develop the theory that describes SBS in a multimode laser with optical breakdown. The breakdown threshold of SF_6 gas for XeCl laser (308nm) is $4GW/cm^2$ above 5×10^5Pa in Ref.[20], from which the breakdown threshold of less than $4GW/cm^2$ for KrF laser (248nm) is inferred. However, the SBS threshold for KrF pump laser with $0.5cm^{-1}$ in SF_6 is at the same level of the breakdown threshold of SF_6 gas which, according to our experimental results, is 2–$12GW/cm^2$ for pressures between 8.5 and 16×10^5Pa. The times for optical breakdown and SBS to build up is 4ns[21] and some 1ns, respectively. It is seen that they occur nearly simultaneously.

We denote E_α the energy absorbed by electrons in the process of optical breakdown, which will be inferred later. The SBS coupled-wave equations neglecting pump bandwidth are expressed as follows:

$$\frac{\partial E_{\rm L}}{\partial z}-\frac{n}{c}\frac{\partial E_{\rm L}}{\partial t}={\rm i}g_{\rm L}\rho E_{\rm S}, \tag{1}$$

$$-\frac{\partial E_{\rm S}}{\partial z}+\frac{n}{c}\frac{\partial E_{\rm S}}{\partial t}=-{\rm i}g_{\rm S}E_{\rm L}E_{\rm L}^*, \tag{2}$$

$$\frac{\partial Q}{\partial t}+\frac{1}{2}\Gamma Q=-{\rm i}g_{\rm a}E_{\rm L}E_{\rm S}^*. \tag{3}$$

From these equations, SBS reflectivity $R(E_0)$ can be calculated.

We assume that the broadband KrF laser spectrum with bandwidth $\Delta\nu$ is of Lorentz linetype $g(\nu)$,

$$g(\nu)=\frac{\Delta\nu/2\pi}{(\nu-\nu_0)^2+(\Delta\nu_{\rm N}/2)^2}, \tag{4}$$

where ν_0 is the central frequency. We assume that the broadband KrF laser spectrum consists of a number of narrow lines. These lines, we suppose in this paper, are coupling with each other to some extent. The energy of each narrow line with bandwidth $\Delta\nu_i$ ($\Delta\nu_i<\Delta\nu_{\rm B}$, $\Delta\nu_{\rm B}$ is Brillouin linewidth) is $E_i=C\cdot(E-E_\alpha)\cdot g(\nu_i)\cdot\Delta\nu_i$. Here C is coupling coefficient. The SBS reflectivity for pump energy E_i is $R(E_i)$. Therefore the SBS reflectivity for broadband pump energy E is

$$R=\sum_{-\infty}^{\infty}\frac{(E-E_\alpha)g(v_i)R(E_i)\Delta v_i}{E}. \tag{5}$$

To calculate E_α we assume that the process of electron amplification starts from the original electron density ρ_0, which is given according to experimental data, by utilizing the classical electron model. The electron amplification rate can be expressed as

$$\frac{{\rm d}\rho}{{\rm d}t}=(\eta-g)\rho, \tag{6}$$

where η is the speed of ionization, g is the speed of electron loss. We have

$$\rho(t)=\rho_0\cdot\exp[(\eta-g)t], \tag{7}$$

where η is proportional to laser power density I. The threshold of optical breakdown $I_{\rm cr}$ can be expressed by the threshold of the speed of ionization $\eta_{\rm cr}$ and g is irrelevant to I. Thus we have

$$\eta_{\rm cr}=g+\tau_{\rm p}^{-1}\log_{\rm e}(\rho_{\rm cr}/\rho_0). \tag{8}$$

When electron density is above $\rho_{\rm cr}(\sim10^8/{\rm cm}^3)$, optical breakdown occurs; $\tau_{\rm p}$ is laser pulse duration.

The electron amplification rate utilizing the classical free electron model is

$$\frac{{\rm d}\xi_0}{{\rm d}t}=\frac{e^2|E|^2\tau}{m(1+\omega^2\tau^2)}, \tag{9}$$

where E is the laser field of frequency ω, τ is the momentum transferring time, e and m are the charge and mass of an electron respectively. The rate of ionization is

$$\eta=\frac{e^2|E|^2\tau}{m\xi(1+\omega^2\tau^2)}, \tag{10}$$

where ξ is energy of ionization. The threshold of optical breakdown is

$$I_{\rm cr}=\frac{mc\varepsilon\xi(1+\omega^2\tau^2)}{2e^2\tau}\left[g+\frac{1}{\tau_{\rm p}}\log_{\rm e}(\rho_{\rm cr}/\rho_0)\right]. \tag{11}$$

The density of electrons at time t is

$$\rho(t) = \rho_0 \cdot \exp\left[\left(\frac{e^2 |E|^2 \tau}{m\xi(1+\omega^2\tau^2)} - g\right)t\right]. \quad (12)$$

The density of electrons in a pulse duration $\tau_{\rm P}$ is

$$\rho = \rho_0 \cdot \exp\left[\left(\frac{e^2 |E|^2 \tau}{m\xi(1+\omega^2\tau^2)} - g\right)\tau_{\rm p}\right]. \quad (13)$$

It is assumed that the incoming pump beam has a Gaussian distribution and propagates in the positive z direction. We denote that the focal point in the SBS cell is at z=0 and the point at which pump power density is equal to $I_{\rm cr}$ is $z = L$ and $z = -L$. We have

$$L = z_{\rm a}\sqrt{\frac{I_0}{I_{\rm cr}} - 1}, \quad (14)$$

where $r_0 = f\theta/2$, $z_{\rm a} = \dfrac{2\pi \cdot r_0^2}{\lambda}$, I_0 is initial pump power density, f, θ, λ are focal length, divergence angle and wave length, respectively. The number of electrons produced by ionization in focal volume with length Δz is

$$N(z) = \rho\pi r_0^2\left(1 + \left(\frac{z}{z_{\rm a}}\right)^2\right)\Delta z. \quad (15)$$

The energy absorbed by an electron is

$$\begin{aligned}\xi_0 =& \frac{e^2 |E(z)|^2 \tau \cdot \tau_{\rm p}}{m(1+\omega^2\tau^2)} \\ =& \frac{2e^2\tau \cdot \tau_{\rm p}}{mc\varepsilon(1+\omega^2\tau^2)} I(z) \\ =& \frac{2e^2\tau \cdot \tau_{\rm p}}{mc\varepsilon(1+\omega^2\tau^2)} \frac{I_0}{1+\left(\dfrac{z}{z_{\rm a}}\right)^2}. \end{aligned} \quad (16)$$

The energy absorbed by electrons in the focal volume with length Δz is

$$E_\alpha(z) = N(z)\cdot\xi_0 = \frac{2\pi e^2\tau r_0^2\tau_{\rm p}}{mc\varepsilon(1+\omega^2\tau^2)}\rho_0 \cdot I_0 \cdot \exp\left[\left(\frac{2e^2\tau I_0}{mc\varepsilon\xi(1+\omega^2\tau^2)\left(1+\left(\dfrac{z}{z_{\rm a}}\right)^2\right)} - g\right)\tau_{\rm p}\right]\cdot\Delta z. \quad (17)$$

The energy absorbed by electrons in the focal volume with length $2L$ within $\tau_{\rm p}$ is

$$E_\alpha = \int_{-L}^{L} N(z)\cdot\xi_0\cdot{\rm d}z = \frac{2\pi e^2\tau r_0^2\tau_{\rm p}}{mc\varepsilon(1+\omega^2\tau^2)}\rho_0\cdot I_0\cdot\int_{-L}^{L}\exp\left[\left(\frac{2e^2\tau I_0}{mc\varepsilon\xi(1+\omega^2\tau^2)\left(1+\left(\dfrac{z}{z_{\rm a}}\right)^2\right)} - g\right)\tau_{\rm p}\right]{\rm d}z, \quad (18)$$

where $\tau = \dfrac{k_1}{p}$, $\omega^2\tau^2 \le 1$ under our experimental conditions. Considering that $\omega^2\tau^2 = 1$, we obtain the expression

$$E_\alpha = \frac{\pi e^2 r_0^2\tau_{\rm p}}{mc\varepsilon p}k_1\rho_0\cdot I_0\cdot\int_{-L}^{L}\exp\left[\left(\frac{k_1}{\xi}\frac{2e^2}{mc\varepsilon\left(1+\left(\dfrac{z}{z_{\rm a}}\right)^2\right)p}I - g\right)\tau_{\rm p}\right]{\rm d}z. \quad (19)$$

2.2. Numerical results

To discuss the threshold and reflectivity of broadband SBS, we select a numerical example. The stationary Brillouin gain coefficient and the phonon lifetime are assumed to be 16.6cm/MW and 1.33ns respectively, which are approximately the parameters in SF_6 at 1.6×10^6Pa. The spontaneous Brillouin linewidth is 0.75GHz. The breakdown threshold of SF_6 gas for KrF laser is assumed to be 4 GW/cm^2. Figure 1 shows the threshold energy versus bandwidth and Fig.2 shows the reflectivity of broadband SBS versus pump energy. The calculated curve shows a strong dependence of SBS threshold on pump bandwidth. Optical breakdown has an increasing influence on SBS threshold with pump bandwidth. It is seen

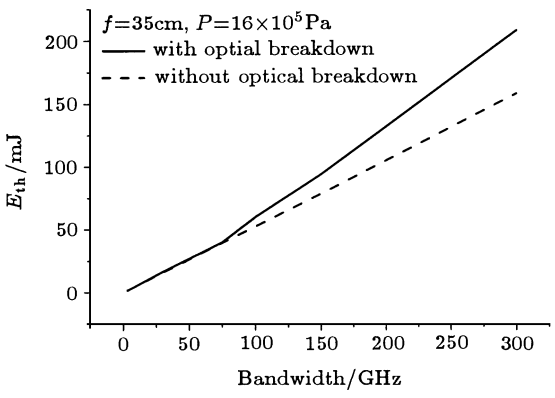


Fig.1. The threshold energy of SBS versus pump bandwidth.

that different peak SBS reflectivity has been obtained with different pump bandwidth and the decrease is observed at high pump energy.

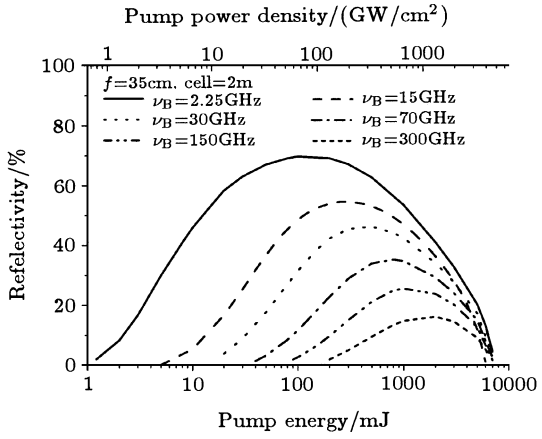


Fig.2. The reflectivity of SBS versus pump energy.

3. Experimental results and analysis

3.1. Experimental apparatus

SBS has been investigated by using the experimental setup shown in Fig.3. The laser system, utilizing a Lambda Physik Model LPX150 KrF laser, provides a laser beam with a linewidth 0.5cm^{-1}(15GHz), a beam divergence angle 0.2mrad, and pulse duration 40ns. The laser beam passes through attenuators, a beamsplitter and then is focused into a 2m long SBS cell containing 1.6×10^6Pa SF_6. The phase-conjugate back reflection produced by the cell is taken through the beamsplitter. Lenses of 15–300cm focal length have been used.

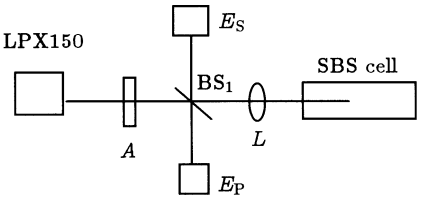


Fig.3. Experimental layout for SBS studies A, attenuators; BS_1, beamsplitter; L, focal length; E_p, energy meter; E_S, energy meter.

3.2. Experimental results and analysis

Pump energy ranging from 2mJ to 2J was observed by placing attenuators in the laser beam. Figures 4 and 5 show the SBS reflectivity as a function of the pump energy in SF_6 at 1.6×10^6Pa. The solid points represent experimental data and the solid curve represents the result of numerical calculation. From Fig.4 it is seen that the energy reflectivity increases at pump energy above 10mJ and the saturation reflectivities 40%, 45% and 32% have been obtained using 15, 35 and 100cm focal lengths, respectively. SBS reflectivity is measured at higher pump energy with 3m focal length in 4m SBS cell length. Comparison between experimental and numerical results is shown in Table 1. We have obtained experimentally 43.8%, 22.6% and 7.3% SBS reflectivity at pump energy 0.69, 1.34 and 2J respectively, while its numerical results are 49.1%, 44.2% and 37.4% respectively. It is discovered that SBS reflectivity decreases at higher pump energy. These results agree well with the numerical calculation results.

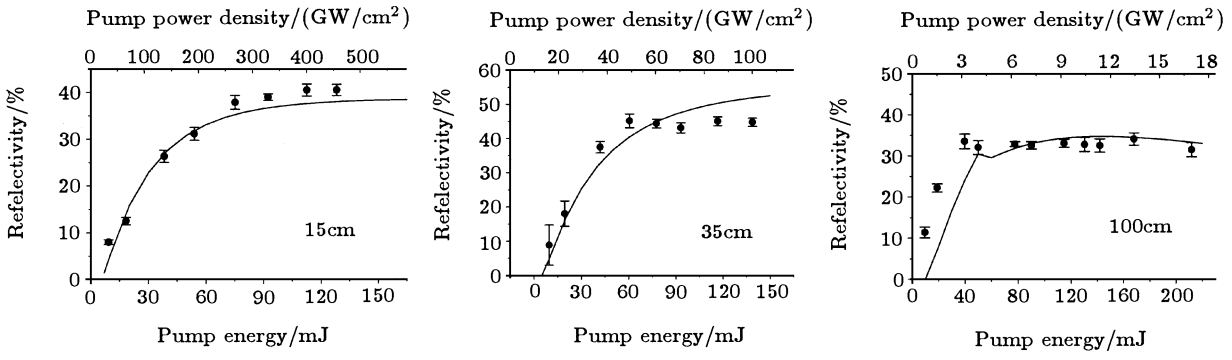


Fig.4. The SBS reflectivity versus pump energy for different focal lengths.

Table 1. Comparison between experimental and numerical results.

Pump energy /J	SBS reflectivity/% (experimental results)	SBS reflectivity/% (numerical results)
0.69	43.8	49.1
1.34	22.6	44.2
2	7.3	37.4

The distributed energy of each line of pump spectrum depends on the pump linewidth. The broader the pump bandwidth, the less the distributed energy of each line of the KrF spectrum. The SBS reflectivity of the broadband pump laser increases slowly compared with that of the narrowband pump laser because the energy of each line of pump spectrum is decreased with increasing pump linewidth, even if these lines couple with each other. The SBS reflectivity has a saturation region and decreases at higher pump energy because of optical breakdown competition.

4. Conclusion

We have developed a SBS model for a multimode pump laser with optical breakdown and have performed experimental investigations. These spectral lines of broadband pump laser are not independent but coupling with each other. The threshold energy increases and reflectivity decreases with increasing pump energy. Optical breakdown causes broadband saturation SBS reflectivity to decrease rapidly at high pump energy.

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