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LETTER TO THE EDITOR

Investigation of optical limiting based on the combination of stimulated Brillouin scattering and carbon nanotube/HT-270 suspension

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Abstract

In order to improve the optical limiting performance based on stimulated Brillouin scattering (SBS), a combination of SBS and carbon nanotube/HT-270 suspension for optical limiting is proposed in this paper. The dependence of output energy of optical limiting based on this hybrid approach on the pump energy is numerically simulated, and validated in Continuum's Nd: YAG seed-injected laser. The results indicate that the output energy based on this hybrid approach shows much better performance compared with that based on single SBS. In this approach, the SBS threshold can be controlled by adjusting the gain coefficient of medium and focal length of the lens, and the threshold of suspension can be controlled by altering the concentration and focal length of the lens, therefore, this hybrid approach to realize optical limiting has great potential in practical application.

Keywords: Hybrid optical limiting; SBS optical limiting; Stimulated Brillouin scattering; Suspension of carbon nanotube/HT-270

INTRODUCTION

In high power laser system, the output power density is so high that it can easily destroy the optical components in the laser system, such as optical crystal, lens and various optical films; therefore, optical protection is crucial for the high power laser system. For safety consideration, the output power of a laser system is usually below the rated power; thereby the efficiency of the laser system is compromised. If protection measures are properly taken, the laser system can output high power and thus the output efficiency is maximized. Since the 1960s, a great deal of methods, including two-photon absorption (Lin *et al.*, 1998), reverse saturated absorption (Kamanina, 1999), nonlinear refraction (Dovgalenko *et al.*, 1996), and optical scattering (Wang & Blau, 2008) have been exploited to realize optical limiting. These studies are mainly aimed at providing protection for eyes and sensors; thereby a low power threshold and small transmissivity are preferred in the case of a high input power. However, for practical application of optical limiting to provide protection for high power laser system, high power density, and high transmissivity are particularly required.

While most research regarding stimulated Brillouin scattering (SBS) has been focused on the characteristics of back-scattered light for phase conjugation and laser pulse compression (Kong *et al.*, 2007; Ostermeyer *et al.*, 2008; Yoshida *et al.*, 2007; Wang *et al.*, 2007; Hasi *et al.*, 2007), there are few studies as to the characteristics of transmitted light. When the pump intensity exceeds the SBS threshold, a strong SBS process takes place through the SBS medium, leading to a quick energy transfer from pump to the Stokes light, and accordingly an optical limiting characteristic in the transmitted light (Lu *et al.*, 2006, 2007; Hasi *et al.*, 2008*a*, 2008*b*). Hasi *et al.* (2008*c*) studied the output energy characteristic of SBS optical limiting. The results show that, although the energy limiting can be readily realized by SBS optical limiting, the performance of energy

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limiting is not so satisfactory due to the insufficient energy transfer from pump to Stokes light, thus presenting a disadvantage to the practical application of SBS optical limiting. To solve the problem, a method of hybrid optical limiting based on the combination of SBS and suspension is proposed in this paper. The dependence of output energy of optical limiting based on this hybrid optical limiting approach on the pump energy is numerically simulated, and validated in Continuum's Nd: YAG seed-injected laser. The results indicate that the output energy based on this hybrid optical limiting approach shows much better optical limiting performance compared with that based on single SBS.

THEORY

In order to improve the optical limiting performance based on SBS, the SBS output is further optically limited by a suspension with a lower threshold. We first define two parameters to characterize the SBS optical limiting: (1) the input energy threshold, which is defined to be the energy value above which the output energy does not increase linearly with input energy. (2) the clamped output energy, which is defined to be the output energy at which the input energy is just above the input energy threshold (Vincent, 2001; Mansour *et al.*, 1992). In the case of a low pump energy, only the SBS optical limiting works. However, as the pump energy increases, the suspension limiting process can be activated if the transmitted power of SBS exceeds the threshold of carbon nanotube/HT-270 optical limiting. Therefore, this hybrid optical limiting approach has an improved performance compared with that based on single SBS in terms of the output energy.

The input energy threshold of SBS optical limiting is determined by the system's exponential gain coefficient G, which is denoted by (Boyd & Rzazewski, 1990):

$$G = gIL, \tag{1}$$

where g is the Brillouin gain coefficient, I is the input power density, and L is the effective interaction length. The system exponential gain coefficient G can be controlled by adjusting g, I, and L. The value of g can be changed by choosing a different medium, while I and L can be altered by adopting lens with different focal lengths. Therefore, the input energy threshold of SBS optical limiting is controllable. If a high threshold of SBS optical limiting is preferred, a medium with small gain coefficient and lens with a long focal length can be utilized. Whereas, a medium with large gain coefficient and lens with a short focal length can be adopted in order to decrease the input energy threshold. So the threshold of SBS can be kept lower than that of suspension.

The carbon nanotube, which rolled up like a hollow cylinder, consists of multiple layers of grapheme sheets. The structure of the carbon nanotube is either a single-wall or a multi-wall depending on the number of the grapheme sheet. The carbon nanotube has been recognized as a good material for broadband optical limiting (Vivien *et al.*, 2000; Sun *et al.*, 1998; Chen *et al.*, 1999; Zhang *et al.*, 2005*a*). The optical limiting property of a carbon nanotube mainly results from its nonlinear scattering during which the laser pulse leads to vaporization and ionization of the carbon nanotube and the generation of the microplasma. The microplasma strongly scatters the incident light, leading to a decrease in the transmitted light energy. At the same time, the carbon nanotube transfers energy to the surrounding liquid and leads to the formation of micron-scale bubble, which in return scatters the incident light and thus further enhances the performance of optical limiting (Durand & Grolier-Mazza, 1998; Zhou *et al.*, 2007). The threshold of the suspension can be controlled by adjusting the concentration and focal length of the lens (Luo *et al.*, 2006). If a high input energy threshold of suspension optical limiting is preferred, a medium with low concentration and lens with a long focal length can be utilized. In contrast, a medium with high concentration and lens with a short focal length can be adopted in order to decrease the input energy threshold.

According to the SBS optical limiting model and the carbon nanotube/HT-270 nonlinear absorption model given (Lu *et al.*, 2003; Zhang *et al.*, 2005*b*), we numerically simulate the curves of output energy of optical limiting based on single SBS and hybrid optical limiting approach and the simulation results are shown in Figure 1. The parameters used in the simulation are as follows: the incident wavelength is 532 nm with a repetition of 1 Hz; the pulse duration is 8 ns with a divergence angle of 0.45 mrad. The medium of the SBS cell is FC-72. The SBS cell length is 40 cm and the focal length of the lens for it is 15 cm. The SBS parameters of media FC-72 and HT-270 are listed in Table 1 (Yoshida *et al.*, 1997; Hasi *et al.*, 2008*d*).

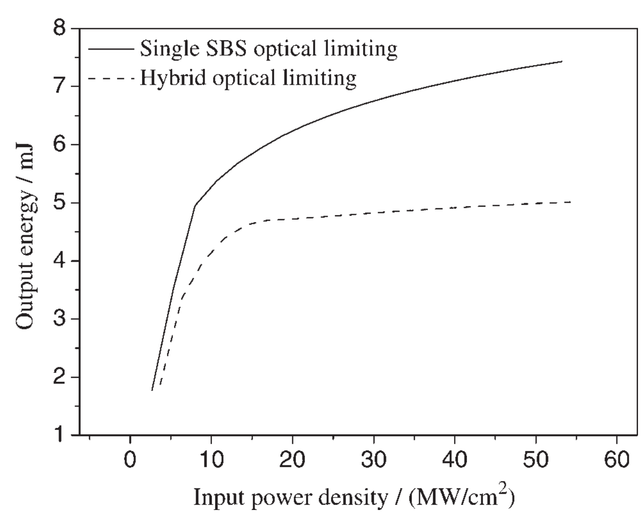

Fig. 1. The simulation result of the dependence of output energy on the input energy based on single SBS optical limiting and hybrid optical limiting.

Table 1. *SBS parameters of FC-72 and HT-270*

Liquid	Absorption coefficient (cm^{-1})	Optical breakdown threshold (GW/cm^2)	SBS gain coefficient (cm/GW)	Phonon lifetime (ns)
FC-72	$<10^{-3}$	>100	6.0	1.2
HT-270	$<10^{-3}$	>100	2.3	0.1

The cuvette filled with suspension has a length of 3 mm and the focal lengths of lens for it is 20 cm. When the pump energy is low, output energy of optical limiting based on hybrid optical limiting approach shows similar performance with that based on single SBS. However, when the pump energy is high and the suspension optical limiting works, the output energy based on hybrid optical limiting approach shows nearly a plateau, demonstrating much better the optical limiting performance.

EXPERIMENT

The experimental setup is shown in Figure 2. The Continuum's Nd: YAG seed-injected laser outputs s-polarized light, which becomes p-polarized after passing the 1/2 wave plate and circular polarized after passing the 1/4 wave plate and then injected into the SBS cell. The SBS system is composed of lens 1 and SBS cell. A polarizer P together with a 1/4 wave plate forms a light isolator, preventing backward SBS light from entering the YAG oscillator. The Stokes light becomes s-polarized after passing the 1/4 wave plate, and is reflected by polarizer P. The divergence beam after the SBS optical limiting becomes parallel after passing the lens 2, and then is focused into the cuvette filled with suspension by the lens 3. The divergence beam after the cuvette becomes parallel after passing the lens 4. The pump pulse energy is altered by adjusting the 1/2 wave plate in the experiment. The energies of incident and transmitted pulse, and Stokes pulse are measured with energy meter OPHIR. Waveforms are detected by PIN photodiode and recorded by oscilloscope TDS684.

The procedure in preparing the carbon nanotube/HT-270 suspension is as follows: first, 20 mg single-wall carbon nanotube is mixed with 50 ml HT-270; second, the mixture is oscillated for 24 h in the ultrasonic oscillator; finally the mixture is filtered by a filter with an aperture of 1.2 μm (Hasi *et al.*, 2004). Figure 3 gives the experimental curves of output energy *versus* input energy based on SBS optical

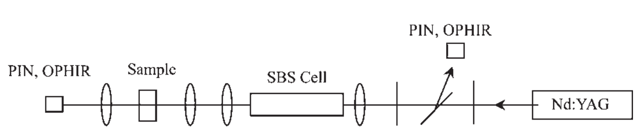

Fig. 2. Experimental setup.

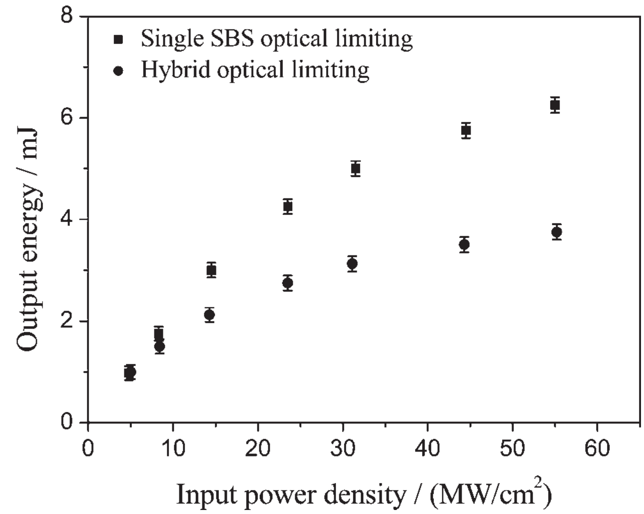

Fig. 3. The dependence of output energy on the input power density based on single SBS optical limiting and hybrid optical limiting.

limiting and hybrid optical limiting, which agree well with the simulation results. It can be seen that only the SBS optical limiting works in the case of a low pump energy. However, as the pump energy increases, the suspension limiting process can be activated. Therefore, the output energy based on hybrid optical limiting shows much better performance compared with that based on single SBS.

CONCLUSIONS

In order to improve the optical limiting performance based on SBS, a method of hybrid optical limiting based on SBS and carbon nanotube/HT-270 suspension is proposed. The dependences of output energy of optical limiting based on single SBS and hybrid scheme of the pump energy are numerically simulated, and validated in Continuum's Nd: YAG seed-injected laser. The results show that only the SBS optical limiting works in the case of a low pump energy. However, as the pump energy increases, the suspension limiting process can be activated if the transmitted power of SBS is still above the carbon nanotube/HT-270 threshold. Therefore, the output energy based on hybrid optical limiting shows much better performance than that based on single SBS. The threshold of SBS can be controlled by adjusting gain coefficient and focal length of the lens; and the threshold of suspension can be controlled by adjusting concentration and focal length of the lens. Therefore, this hybrid approach to realize optical limiting has great potential in practical application.

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