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Spectral behavior of amplified back-scattered Stokes pulse in two-cell phase conjugating mirror

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ABSTRACT

In this paper, the spectral behavior of two-cell phase conjugating mirror (PCM) with a two-pass Nd:YAG amplifier has been analyzed experimentally and theoretically. For this purpose, input intensity with single and multi-longitudinal modes has been investigated. The numerical model is based on focused geometry model (1+1 dimension) equations of Stokes back-scattered intensity and acoustic waves, for two-cell generator-amplifier phase conjugating mirror with proper boundary conditions that are solved simultaneously with the rate equations of Nd:YAG optical amplifier. Results of the Fourier analysis of the amplified intensity show considerable differences between Fourier amplitudes of the amplifier equipped with PCM and a two-pass amplifier with a conventional mirror under the same output energy. The amplifier with PCM has a completely filtered and different spectral behavior with clearly reduction of the beating between Fourier components of input optical field. Calculations show that the filtering of Fourier components by a PCM is done more effectively with lower pumping energy.

1. Introduction

Stimulated Brillouin scattering (SBS) of laser radiation applied for building phase conjugating mirrors in laser systems [1–21] and thus can be utilized to compensate the wavefront distortion [1–5], and phase restoration. SBS is also applied to compress laser pulses [6–12]. The phase-conjugation also considered as a promising phase-locking tool for solid state gain media including large mode area Yb-fiber array laser amplifiers [13].

For both SBS phase conjugation (SBS-PC) and SBS pulse compressor, two general types of cell-arrangements apply: single cell SBS generator [2,6,8–10,14–19] and two-cell SBS generator-amplifier [4,5,7,20,21]. In two SBS cells configuration, laser beam is focused into the generator cell (Gen-cell) and then the back-scattered Stokes and acoustic fields grow from noise in generator. The Stokes seed light enters the amplifier cell (Amp-cell) where it interacts with pump light and amplifies dramatically, meanwhile the pulse width is became narrower. Due to the lower pump intensity relative to SBS threshold and increasing the interaction length without undesired nonlinearity in SBS Amp-cell, the energy conversion efficiency is enhanced in comparison to single SBS cell [5,20].

By using back mirror in two pass high power laser amplifier systems, output energy and energy extraction efficiency increases, but detrimental nonlinearities including birefringence, self-focusing and Kerr effect which cause to wavefront aberration and temporal pulse shape deformation are also enhanced [6]. While by using phase conjugating mirror, spatial beam quality can be improved after two-pass amplification.

The effect of threshold intensity in Gen-cell and physical characteristics of SBS materials lead to have different temporal pulse shape and different spectral behavior respect to original pump pulse. This noticeable property is very important for the Stokes pulse shape in multi-mode laser pump pulse that is investigated in this paper.

Stimulated Brillouin scattering has been extensively studied in single-mode [3–6,19,20] and multi-mode laser pump pulses [3,14–16] both theoretically and experimentally. This paper presents the effect of laser longitudinal mode structure on the spectral features of SBS reflectivity and scattered pulse shape. These properties of PCM are examined in a two-pass amplifier (TPA) for single-mode and multi-mode pump pulse with some different approach to study the spectral behavior of the amplified Brillouin back-scattered field. Then, the results have been compared with the characteristics of reflected pulse from a conventional mirror (CM).

This paper has been arranged as follows: first, the experimental setup has been described that is consist of a ring laser oscillator (OSC) and two-pass Nd:YAG amplifier (AMP) which is equipped with a two-cell SBS mirror. Then, the numerical model that is based upon rate equations of optical and acoustic fields, and using an optical field with longitudinal single, two and multi-mode structure that its spot size follows the laws of Gaussian beam

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propagation is explained. Results appeared and compared afterwards. The paper is concluded in last section.

2. Experimental setup

To study spectral behavior and temporal pulse shape of scattered intensity from phase conjugating mirror, we have used a Nd:YAG passively *Q*-switched non-planar unidirectional ring resonator [22]. To control the number of longitudinal modes, two etalons(ET_1, ET_2) with thickness $t_1=6$ mm, $t_2=15$ mm, and reflectivity $R_1=36\%$ and $R_2=65\%$ at 1064 nm are utilized. Mode separation in the ring resonator is twice of a linear resonator with an equal optical length ($\Delta\nu_{\text{ring}}=2\Delta\nu_{\text{linear}}$), hence ring type resonator is more suitable to produce single longitudinal mode laser oscillation. The optical length of ring resonator is $L_{\text{opt}}=1250$ mm, and then the mode separation in our setup is $\Delta\nu_{\text{ring}}=c/L_{\text{opt}}=240$ MHz.

We have adjusted angle of normal of both ET_1 and ET_2 respect to optical axes of resonator to have single longitudinal mode. By eliminating one of the etalons, we have two or three mode structure and by eliminating both etalons we have a multi-longitudinal field from OSC. A Dove prism (DP) with color center is placed inside the OSC to make a passively *Q*-switched non-planar ring resonator. The non-planarity is considerably increased the stability of laser resonator and the misalignment tolerance of mirrors. The DP has Brewster's angle cut which leads to have a polarized beam and decreasing optical losses. Moreover, we used an internal aperture (AP) of 2.5 mm diameter to achieve TEM_{00} transversal mode. All of the mirrors (M_i) are total reflectors, and the reflectivity of beam splitter (BS) is 50% at 1064 nm.

In all of the measurements, the pumping energy delivered to flash lamp of oscillator is 29 J, which results about 15 mJ output energy. The shot-to-shot beam profiles were almost the same and nearly Gaussian with 2.5 mm diameter. The OSC beam divergence is 0.43 mrad and pulse duration ~28 ns (FWHM). A very low pulse repetition rate 0.05 Hz, has been selected to avoid thermal effects and to achieve a good stability. More technical details of the oscillator are presented in [22].

The polarization state of the oscillator output beam is linearized by using a half wave plate and a polarizing beam splitter (Glan-Thompson prism) (POL) after the OSC, which results the amplifier input energy decreases to $\sim 11\pm0.5$ mJ. The amplifier (AMP) active medium of two-pass amplifier (TPA) is a Nd:YAG rod with 8 mm diameter and 10 cm length. In order to maximize the AMP output energy, 100 μs time delay has been applied between AMP and OSC flash lamp triggers.

The quarter wave plate axis for two pass amplifier was oriented with 45° respect to plane of polarization of laser field to convert the linear polarization to circularly, which propagates inside the SBS cells. The pumping pulse is focused by convex lenses (FL_1 and FL_2) into the cells containing acetone of 99.8% purity as the nonlinear medium.

The first pass amplified output beam from AMP, enters to PCM which consist of SBS Amp-cell and SBS Gen-cell that is schematically depicted in Fig. 1. The SBS Gen-cell has $L_1=312$ mm length and 14 mm effective aperture equipped with a convex focusing lens before the generator with focal length $f_1=400$ mm and anti-reflection coating at 1064 nm. Distance of f_1 from SBS Gen-cell is $D_1=185$ mm. The length of SBS Amp-cell is $L_2=435$ mm with 25 mm effective diameter. A convex focusing lens of focal length $f_2=1000$ mm before SBS Amp-cell was used. Distances of lens FL_1 from the SBS Amp-cell end window, and lens FL_2 from SBS Amp-cell entrance window are $D_2=155$ mm, and $D_3=80$ mm, respectively. The back scattered Stokes beam passes through QWP and AMP, and is out coupled from AMP by POL. The pulse shape and fast Fourier transform (FFT) of pump and Stokes beams have been measured by a combination of fast photodiode with 0.1 ns response time and Tektronix digital oscilloscope TDS3052B with 500 MHz bandwidth and a thin blank glass plates (*P*) with 5% reflectivity. A neutral density filter (ND) with appropriate optical density was used in front of the photodiode to attenuate beam intensity. The energies are measured by a Joule meter (Jm) as depicted in Fig. 1.

3. Numerical model

We have used a focused geometry model (1+1D model) [23,24] for simulation of two-cell, phase conjugating mirror accompanied by the classical model of laser amplifier [25]. The OSC pulse shape is equal to experimental oscillator pulse with the same pulse-width, number of longitudinal modes and pulse

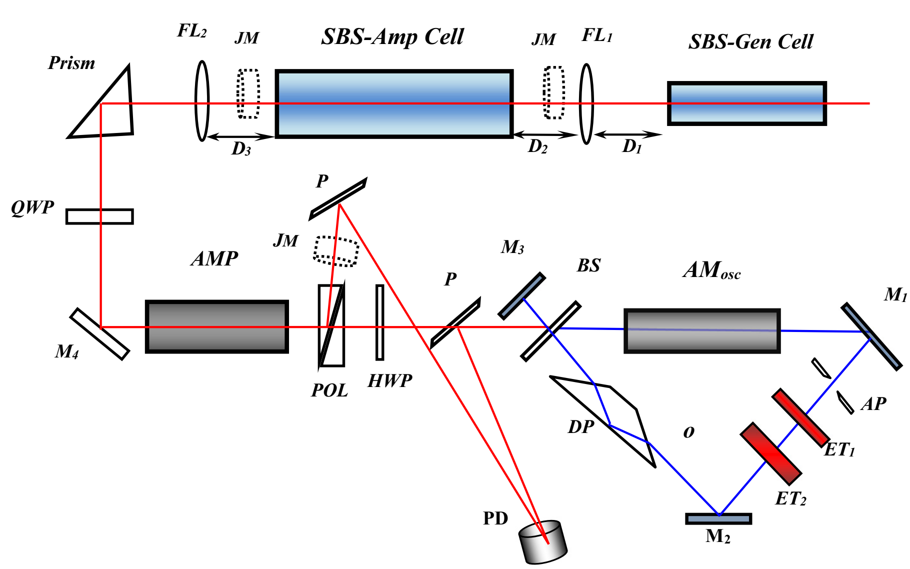

Fig. 1. Schematic of experimental setup for studying stimulated Brillouin back scattering with two SBS cells. M=mirror; AP=aperture; ET=etalon; DP=color centered Dove prism; DP=50% beam splitter at 45°; AM=active medium; P=blank glass plate with 5% reflectivity; PD=fast photo-diode; HWP=half wave plate; GT=Glan-Thompson prism as polarizing beam splitter; QWP=quarter wave plate; FL=convex lens; JM=energy meter. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)