Laser Original

Passive Q-Switching of a Flashlamp-Pumped Ti:Sapphire Laser with a Stimulated Brillouin Scattering Nonlinear Mirror

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Passive Q-switching operation of a flashlamp-pumped Ti:sapphire laser utilizing an intracavity telescope filled with a liquid Brillouin medium, $C_2Cl_3F_3$, is described. A narrow linewidth seed pulse is generated with an auxiliary resonator consisting of a grazing incidence grating to reduce the stimulated Brillouin scattering threshold. The magnification of a telescope and an auxiliary resonator length were designed so that a large TEM₀₀ mode volume is obtained in the gain medium. When the Q-switch timing was optimized by inserting a loss in the auxiliary resonator, an output energy of nearly 40 mJ in a ~ 20 -ns pulse was obtained.

Key Words: Ti:sapphire laser, Flashlamp pumping, SBS mirror, Q-switch

1. Introduction

Since titanium-doped sapphire (Ti:sapphire) exhibits broad absorption band in the visible region in the spectrum and excellent thermal and mechanical properties, flashlamp-pumped Ti:sapphire lasers offer the capability of scaling to higher energies while keeping a relatively simple and compact device. Up to 6.5 J output was reported by Brown and Fisher with short current pulse ($2 \mu s$ FWHM) flashlamps¹⁾. Recently, high average power of 220 W was demonstrated by Hoffstädt with a total efficiency of 1.9%²⁾. Simultaneous two-wavelength operation was also achieved by the use of a relatively large active medium diameter³⁾. Tunable Q-switching of Ti:sapphire lasers is of particular interest because it provides short duration laser pulses required for nonlinear studies, medicine, spectroscopy, and other various applications. Active Q-switching using electro-optic or acousto-optic devices is easy to control, and

thus widely used for flashlamp-pumped Ti:sapphire lasers⁴⁾. However, passive Q-switching using only a few intracavity passive elements such as saturable absorber is more simple and economical. Recently, $Cr^{4+} : Gd_3Sc_2Ga_3O_{12}$ crystals⁵⁾ or semiconductor-doped glasses⁶⁾ had been demonstrated to be a broad-band saturable absorber in the wavelength range of Ti:sapphire lasers. Actually, they have been demonstrated only for a flashlamp pumped $Cr:LiSrAlF_6$ lasers.

While, passive Q-switching utilizing an intensity-dependent nonlinear mirror based on stimulated Brillouin scattering (SBS) had been demonstrated in Nd:YAG lasers⁷⁻⁹⁾. In laser oscillators, the SBS mirror usually replaces the highly reflecting mirror used for conventional cavities. To overcome the SBS threshold, one usually uses an auxiliary resonator in addition to the main SBS laser resonator. In this letter, we investigate the applicability of an intracavity SBS cell to Q-switch the flashlamp-pumped

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Fig. 1 Schematic of a SBS Q-switch resonator for a flashlamp pumped Ti:sapphire laser. OC: T30% @780-840 nm output coupler G: 1800/mm, Au-coated holographic grating TR: total reflector @680-950 nm L_1 : $f=100$ mm lens L_2 : $f=35$ mm lens ND: ND filter.

Ti:sapphire laser, which exhibits much broader linewidth in free-running than Nd:YAG lasers. To our knowledge, this is a first passive Q-switching operation for a flashlamp-pumped Ti:sapphire laser.

2. Experiments and discussion

The experimental setup of the SBS Q-switched Ti:sapphire laser is shown in Fig. 1. The main resonator consists of a SBS nonlinear mirror and a planar output coupler ($T = 30\%$ at 780-840, nm). In order to obtain high reflectivities with a SBS mirror, the laser linewidth must be narrow enough relative to the SBS linewidth. Therefore, we generate a narrow linewidth seed laser for initiating the acoustic wave in the SBS medium, in a grazing-incidence grating auxiliary resonator formed by a gold-coated holographic grating with 1800, grooves/mm, a broadband dielectric-coated planar total reflector (670-950, nm) as a tuning mirror, and the output coupler. Since ideally, the auxiliary resonator is optically isolated from the main resonator once the SBS mirror turns on and reaches higher reflectivities, the energy load on the tuning elements could be decreased. Moreover, since the seed pulse is allowed to build up in the low-Q cavity, a grazing incidence grating configuration, which exhibits a relatively large optical loss, is still applicable for this scheme.

The incident angle of the light to the grating

was set to 80° to obtain higher diffraction efficiencies at relatively low optical gains ($g_0 l \sim 1.75$) offered by the flashlamp-pumped Ti:sapphire laser. This smaller incident angle compared with typical angles of $85^\circ \sim 89^\circ$ in pulsed dye lasers degrades wavelength dispersion at the grating. However, a relatively long build-up time of ~ 100 ns for lasing in the flashlamp-pumped Ti:sapphire laser allows a large number of cavity round trips before lasing¹⁰⁾. This round-trip passes can compensate for spectrum narrowing. In our previous experiments, utilizing the grazing incidence grating resonator with the incident angle of 82° , we obtained a laser linewidth of ~ 7 GHz at the center wavelength of 800 nm with a pulse energy of 100 mJ in a series of relaxation oscillations with a typical duration of 100 ns FWHM, and separated by ~ 200 ns¹⁰⁾ (Fig. 2(b)).

The detail of laser head design used in our experiments had been described elsewhere^{10,11)}. The six flashlamps with 10.2-cm arc length were arranged cylindrically around a Ti:sapphire rod in a closed-coupled configuration. The pulse width of the flashlamp light is $3 \mu\text{s}$, which is comparable with the upper state lifetime 3.2 μs of Ti:sapphire¹²⁾. The Ti:sapphire rod is 6.35-mm-diameter and 7.62-cm-length at a Ti concentration of $[\text{Ti}] = 0.1$ wt%. The nominal figure of merit of the Ti:sapphire rod was measured to ~ 90 .

Fig. 2 Temporal profile of the typical (a) flashlamp light, (b) free-running laser pulse with a grazing-incidence grating resonator, and (c) SBS Q-switched laser pulse.

Fig. 3 Temporal profile of the typical SBS Q-switched laser pulse.

The SBS cell is formed with a stainless steel flexible tube and two lenses as windows without

coating. This cell itself acts as an intracavity telescope for the auxiliary resonator, which defines a TEM_{00} mode volume. The telescope magnification M of 2.86 and the auxiliary resonator length of 120 cm were selected so that the TEM_{00} beam waist of the auxiliary resonator is close to the gain medium radius¹³⁾. The telescope was slightly defocused to stabilize the beam waist against the change in the telescope length¹³⁾. The beam waist is 1.45 mm. When we chose the beam waist size of 2mm, lasing was not obtained. It is presumably due to larger diffraction loss of the cavity mode.

We used $C_2Cl_3F_3$ (freon-113) liquid as a SBS medium because of its high Brillouin gain, high breakdown threshold, and excellent chemical stability¹⁴⁾. The Brillouin shift ν_B and linewidth $\Delta \nu_B$ of freon-113 at $\lambda = 790$ nm were estimated from the reported values at $\lambda = 532$ nm¹⁵⁾ to 2.5 GHz and 400 MHz, respectively. The longitudinal and transverse mode structures of the two coupled resonators of the auxiliary and SBS-based oscillators have to be matched, respectively, for a smooth transition of the light oscillation from one resonator to the other. Moreover, the most effective excitation of SBS is obtainable if the auxiliary oscillator is tuned to the Brillouin shift ν_B . To satisfy these conditions, we chose the length of the auxiliary resonator and the SBS resonator to 120 cm ($\Delta \nu = 125$ MHz) and 60 cm ($\Delta \nu = 250$ MHz), respectively.

Theoretically, the SBS resonator has double round-trip transversal eigenmodes, each of which is characterized by two beam waists: one is close to that of the seed beam, and the other is about ten times as small as that of the seed¹⁶⁾. However, a fraction of the double round-trip eigenmode beam, which leaks out of the SBS mirror and then reflects back from the grating to the SBS resonator through the SBS cell, turns

to far from the eigenmode. Therefore, the spatial pattern of the output beam is a superposition of these two beams.

During the early stage of experiments, we used an intracavity telescope with $M = 1$. We obtained a spatial profile of the output beam composed of TEM_{00} and TEM_{01} modes. The time histories of the output pulse consisted of two sequential pulses separated by ~ 800 ns with more energy in the second pulse. From the output beam pattern, the second pulse seems to correspond to the TEM_{01} mode.

After the optimization of all parameters at the telescope magnification $M = 2.86$, stable Q-switching was observed. Figure 2 shows SBS Q-switch timing relative to a typical free-running laser pulse with the normal grazing-incidence grating resonator and the flashlamp light temporal profile. The SBS-based Q-switch pulse was measured with a biplanar photo tube (Hamamatsu, R1193U-02) and a digital oscilloscope (Sony Tektronix, TDS350: 200 MHz band width). A typical SBS-based Q-switch pulse is shown in Fig. 3. The modulation of this pulse at a period of ~ 4 ns corresponds to the round-trip time of the SBS resonator. A modulation corresponding to the inverse Brillouin shift of 2.5 GHz cannot be resolved in our diagnostics. The laser linewidth of 33 GHz was measured with a solid etalon ($FSR = 50$ GHz) and a photodiode array. Since the round trip time in the SBS resonator, estimated from the laser output pulse width, is ~ 4 , the maximum frequency broadening induced by SBS is ~ 10 GHz. Therefore, the laser linewidth is mainly defined by the seed pulse linewidth generated in the auxiliary resonator.

We inserted a neutral-density (ND) filter in the auxiliary resonator to optimize the Q-switching timing. The laser output energy and the Q-switching timing were varied with chang-

Table I Laser energy and relative delay of Q-switching for various transmissions of ND filter inserted in the auxiliary resonator. The laser wavelength was tuned to 790 nm.

T of ND Filter [%]	100	70	50	35
Pulse Energy [mJ]	12	26	25	0
Relative Delay Time [ns]	0	200	500	600
Pulse Width [ns]	15	18	16	—

ing the ND filter transmission as shown in Table I. When the pair of grating and total reflector was replaced by a normal flat reflector, therefore, there was no linewidth narrowing function, we could not obtain any Q-switch pulses. Therefore, generation of a narrow linewidth seed pulse is an essential factor in the Q-switch operation of Ti:sapphire laser with the SBS nonlinear mirror. When the auxiliary resonator was tuned to $\lambda = 790$ nm, the Q-switched laser energy of 26 mJ was obtained. We obtained a laser pulse, with almost the same energy extracted from the output coupler, as a zero-order diffraction from the grating. The laser pulse width of the zero-order diffraction is also ~ 15 ns (FWHM). By using a zero-order diffraction efficiency of $\sim 50\%$, which we measured in separate experiments, we can estimate the effective reflectivity of the SBS mirror to $\sim 50\%$. This low reflectivity is attributed to the broad linewidth of the seed pulse relative to $\Delta\nu_B$. It should be also noteworthy that the ND filter inserted in the auxiliary resonator is limiting the Q-switched output energy at such the low SBS mirror reflectivity. When a Fabry-Perot etalon ($FSR = 51$ GHz) was placed in the auxiliary cavity, we obtained the highest output energy of 40 mJ.

The spatial beam profile was measured with a spherical lens ($f = 600$ mm) and a CCD camera as shown in Fig. 4.

The beam divergence estimated from the beam pattern at an output energy of 26 mJ is

Fig. 4 Typical spatial beam profile of an SBS Q-switched laser at the focus of a $f=600$ mm lens. (a) output energy 26 mJ; (b) output energy 2 mJ.

nearly 10 times as large as that of a diffraction limited (DL) beam, while at lower output energy of ~ 2 mJ, a spatial pattern near the fundamental mode was obtained. This beam divergence of $10 \times \text{DL}$ is almost the same as that obtained in normal lasing with a grazing-incidence grating cavity¹⁰.

From a practical point of view, conjugation fidelity is the another important parameter that characterizes the performance of a SBS nonlinear mirror. The relatively large beam divergence obtained from the present resonator indi-

cates a low conjugation fidelity. We considered thermal effects by pump laser absorption. Localized heating in the SBS near the focus might result in poor fidelity without affecting its reflectivity. We measured the focal plane heating by detecting a He-Ne laser beam, which was injected into the SBS cell and carefully aligned to follow the same path as the Ti:sapphire laser beam. When a refractive-index change takes place in the SBS cell, the far-field intensity of the transmitted He-Ne laser decreases. A clear He-Ne laser blooming was observed even at the pump energies much lower than the critical energy $W_{\text{cr}} = 2\pi \rho C_p / (\partial n / \partial T)_p \alpha k^2$, where ρ , C_p , n , T , and α are the density, the specific heat, the refraction index, the temperature and the optical absorption coefficient of the medium, respectively, and $k = \pi / \lambda$. λ is the wavelength of the incident laser beam) of 15 J reported for $1 \mu\text{m}$ light¹⁷. The critical energy is defined for TEM₀₀ mode beam by the energy required for the energy density at the focal waist being reduced to one half due to the change in the refractive index¹⁴. Since we are convinced that there is no strong absorption near 780 nm wavelength in $\text{C}_2\text{Cl}_3\text{F}_3$, this thermal blooming might be caused by the optical absorption relating with some impurities. Proper purification processes for freon-113 liquid to decrease the impurities¹⁷ will eliminate the localized heating near the focus, and thus achieve better beam qualities. Another solution of the thermal blooming is the use of gaseous SBS media such as SF_6 , although extremely high pressure range (> 10 atm) required to obtain a low threshold laser power for SBS generation make the system less easy to handle.

Even if we could eliminate the thermal effect resulting in the poor fidelity, accumulated effects of imperfect phase-conjugated wave generation at each the SBS mirror reflection on the

output beam quality, when it is used as an cavity laser mirror, are still an open question. It needs more studies whether wavefront distortions caused in active gain materials, for example when the laser is operated under high energy loading, can be compensated with the SBS cavity mirror.

It is also noteworthy that even with a perfect phase-conjugation mirror, there is no way to undo the phase aberration that caused in the auxiliary cavity section on the seed beam prior to initiation of the SBS reflectance. Therefore, the auxiliary cavity must be carefully designed to minimize the phase aberration caused by each optical component in the cavity.

3. Conclusion

In conclusion, passive Q-switching with an intracavity SBS cell was demonstrated for the first time for a broad-band Ti:sapphire laser. The auxiliary resonator consisting of a grazing-incidence grating generates a narrow linewidth seed pulse and initiates SBS in $C_2Cl_3F_3$ medium. By carefully designing the internal telescope to obtain a maximum TEM_{00} mode volume, we obtained a highest output energy of 40 mJ with a pulse width of 15 ns (FWHM). For better beam qualities, one needs to achieve both high phase-conjugating mirror reflectivities and fidel-

ities with narrower linewidth seed pulses.

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