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Active-passive mode-locked Nd:YAG laser with a saturable absorber centered in a Fabry–Perot cavity

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We have found that the use of a saturable dye cell, placed at the center of a Fabry–Perot cavity, produced more stable mode-locked pulses without satellite pulses than a contacted dye cell configuration in active-passive mode locking of a pulsed Nd:YAG laser. The mode-locked pulse width was measured to be 23 ps and the energy stability of its frequency-doubled output was within ±3%. The displacement of the dye cell position from the exact center of the cavity was found not to be critical.

Passively mode-locked solid-state lasers using a saturable dye have been extensively utilized as picosecond sources because they can produce short, high-energy pulses with ease of operation and low cost, but have poor shot-to-shot stability and reproducibility which result from the inherent statistical characteristics in the buildup of the mode-locked pulses.[1] To overcome this problem, a great deal of effort has been dedicated to active-passive mode locking, of which many representative schemes[2–4] are now in common use. In a Fabry–Perot cavity configuration, it is essential to utilize a relatively thin dye cell in optical contact with one of the cavity mirrors[5] in order to obtain better shot-to-shot stability and shorter pulses for both purely passive and active-passive mode locking. We report here the use of a noncontacted dye cell placed at the center of a Fabry–Perot cavity for the active-passive mode locking of a pulsed Nd:YAG laser ($\lambda = 1.064\ \mu$m). This scheme gives more stable mode-locked pulses which are comparable to or better than those obtained by using a contacted dye cell.

For purely passive mode locking of a giant pulse solid-state laser with a Fabry–Perot cavity, the dye cell should never be placed at the center of the cavity because such a configuration gives the maximum probability of the generation of satellite pulses, which result in a large instability of the laser output.[6] However, if an active loss modulator, such as an acousto-optic modulator, is additionally introduced into this configuration to produce active-passive mode locking, then the satellite pulses, which occur at half of the cavity round trip time after the main mode-locked pulses,[7] can be suppressed completely. This occurs because the satellite pulses experience maximum loss at the active modulator. Also, the dye cell position need not be at the exact center of the cavity since the half width of the loss of the active modulator is considerably longer than the mode-locked pulse width. In addition, there is no probability of pulses overlapping in the dye cell, except for the suppressed satellite pulses, as in a ring cavity. Therefore, this configuration is expected to produce mode-locked pulses with better stability and shorter pulse width which are comparable to or better than those obtained by using a contacted dye cell. Some practical advantages using a noncontacted dye cell are that the problems associated with the fabrication of a contacted dye cell can be avoided and this configuration can utilize a relatively thick static dye cell with a photochemically more stable dye. Another scheme using a noncontacted dye cell in a cavity is colliding pulse mode locking with an antiresonant ring cavity[8] to obtain shorter pulses. In this case, since the two pulses which are divided from a single pulse must collide in the dye cell, the dye cell position must be at the exact center of the antiresonant ring, which makes the system more difficult to align when an active modulator is incorporated.[9]

The present experimental setup is schematically shown in Fig. 1. The laser cavity consists of a rear mirror with 3 m radius of curvature and 99.5% reflectivity and a flat output mirror with 60% reflectivity. The cavity round trip time is 7.2 ns. The Nd:YAG rod (Kigre, Inc.) has a 6 mm diameter and is 76 mm long, is a Brewster/Brewster type, and is pumped by a linear Xe flashlamp housed in a gold-plated elliptical reflector. A 2-mm-diam aperture is inserted next to the rear mirror to select the TEM_{00} mode. The active loss modulator is an acousto-optic modulator (AOM) (IntraAction Corp. ML-70D) operated at 69.824 MHz rf (139.65 MHz optical) by a frequency synthesizer driving 6 W of rf power (IntraAction Corp. MLE-6A). The temperature is fixed at 27 °C by circulating temperature-controlled water. The saturable absorber used is Kodak No. 9860 dye dissolved in 1,2-dichloroethane with a transmission of 62% at 1.06 μm and flows through a 1-mm-thick cell with wedged cell windows. The dye cell centered in the cavity is mounted on a translation stage to investigate the effect of the displacement of the dye cell position from the exact center of the cavity.

The mode-locked pulse train emitted by the laser is divided into two parts: one part is sent to an autocorrelator to measure the pulse width and the other to a doubling KH_2PO_4 (KDP) crystal to monitor the mode-locked pulses through a second-harmonic generation (SHG). The autocorrelator, which utilizes a well-known SHG method,[10] measures the autocorrelation trace with the background by using a collinear type I KDP crystal. The intensity of the second-harmonic pulse is integrated by using a photodiode with a long response time ($\sim 1\ \mu$s) under a low second-harmonic conversion efficiency. The output reflects the total quality of the mode-locked pulse train since the second-harmonic intensity is dependent on the

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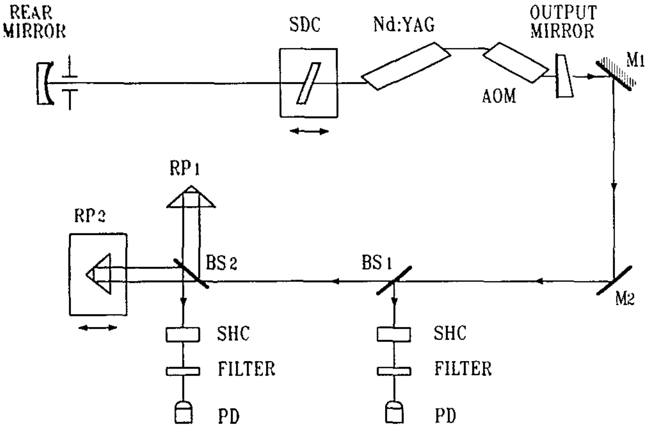

FIG. 1. Experimental setup. The saturable dye cell (SDC), mounted on a translation stage, is placed at the center of the cavity. AOM: acousto-optic modulator, M_1,M_2: mirrors, SHC: doubling KH_2PO_4 crystal, RP_1,RP_2: right-angle prisms, PD: photodiode.

pulse width and the spot size as well as the energy of a laser pulse.[11]

As expected, our laser displays the typical characteristics of active-passive mode locking, i.e., a sharp lasing threshold and a high success rate of mode locking (~ 1 miss during 200 shots). Figure 2 shows a typical mode-locked pulse train detected by using a *p-i-n* photodiode (~ 1 ns rise time, > 2 ns fall time) and a Tektronix 7934 storage oscilloscope (7A19 Amplifier: 0.8 ns rise time). It is apparent that the satellite pulses are completely eliminated, which are frequently observed when attempting the purely passive mode locking. The energy of the mode-locked pulse train was measured to be 4.30±0.08 mJ (±1.9%).

Figure 3(b) is the autocorrelation trace of the mode-locked pulse. Assuming a Gaussian pulse shape, the pulse width is calculated to be 23 ps (autocorrelation width = 32 ps). The second-harmonic intensity, which is integrated by using a photodiode, is plotted versus 100 laser shots in Fig. 4(b) to show the shot-to-shot stability of the mode-locked pulse train. The standard deviation of the second-harmonic signal is ±3%. These results are comparable to those obtained by using a contacted dye cell,[3,4] but the second-harmonic signal is more stable in our case. When the dye cell was moved ±3 cm (limit of travel of the present translation stage) from the center of the cavity, the pulse widths remain unchanged within the standard deviation of the second-harmonic signals, which are in the range of ±3–5%.

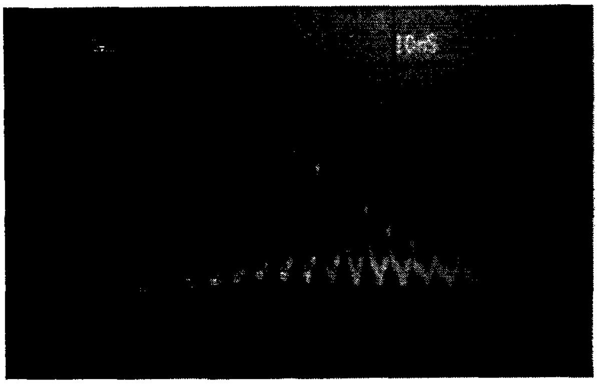

FIG. 2. Active-passive mode-locked pulse train when the dye cell is centered in the cavity (10 ns/div).

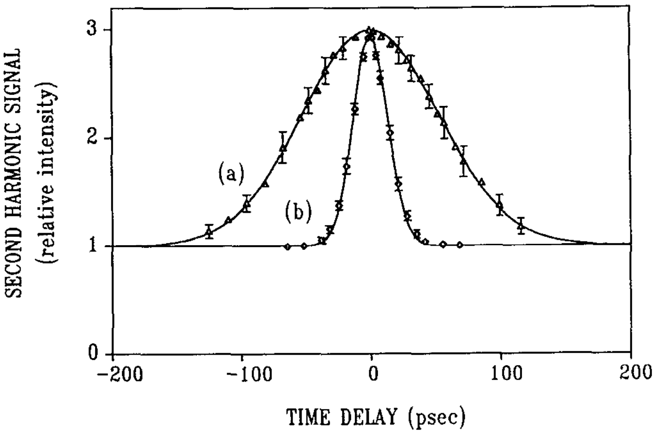

FIG. 3. Autocorrelation traces of the mode-locked pulses when the dye cell is near the rear mirror (a) and at the center of the cavity (b) (Solid curves: Gaussian fittings).

For comparison, the dye cell was placed near the rear mirror (~ 10 mm from it) where the effect of satellite pulses was expected to be clearly evident, since they would experience minimum loss in the active modulator, with the ratio of the beam spot sizes in the dye cell and the Nd:YAG rod held constant. In this case, the mode-locked pulses have a much longer pulse width of 88 ps [Fig. 3(a)] and a lesser degree of stability of ±11% [Fig. 4(a)]. Therefore, these experimental results confirm that the improved results obtained with the dye cell centered in the

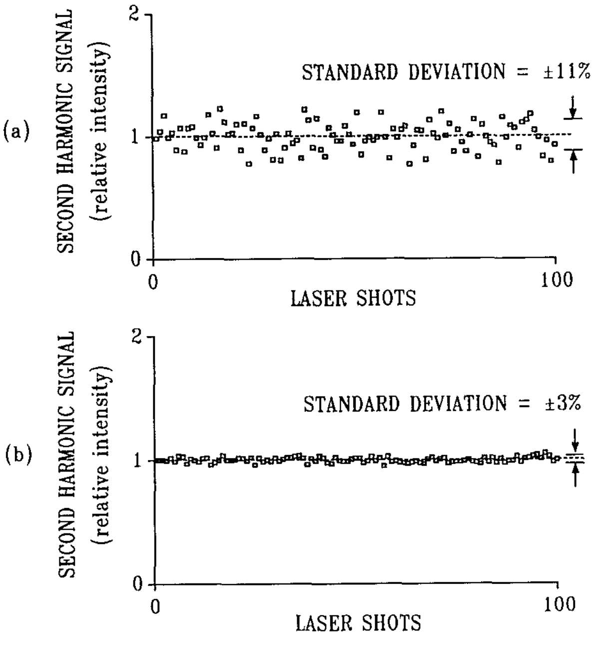

FIG. 4. Integrated second-harmonic intensity plotted vs 100 laser shots to show the shot-to-shot stability of the mode-locked pulse train when the dye cell is near the rear mirror (a) and at the center of the cavity (b).

cavity is attributed to the suppression of the satellite pulses by the maximum loss of the active modulator, as previously mentioned.

In conclusion, we have shown that the use of a noncontacted dye cell centrally placed in a Fabry–Perot cavity produces more stable mode-locked pulses compared to those obtained by a contacted dye cell configuration, for an active-passive mode-locked Nd:YAG laser. The pulse width was 23 ps and the energy stability of the frequency-doubled pulse train was within ±3%.

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