Mode-locking operation of a pulsed Nd:YAG laser with F_2^-:LiF color-center crystal in a dual configuration

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Passive stable mode locking of a pulsed Nd:YAG laser was achieved with a long-decay-time saturable absorber in a coupled-cavity longitudinal scheme. In this configuration the saturable absorber (LiF:F_2^-) also behaves as an active medium in intracavity pumping and is the load for the Nd laser. This arrangement provides proper lasing conditions for the F_2^- color centers so that the cavity photon lifetime of the color centers is much shorter than the cavity round-trip time of the Nd laser. In this way the Nd pulses are simultaneously Q switched and mode locked. The pulses show a stable temporal profile, with an envelope of 160 ns and a train of mode-locked pulses of less than 200-ps duration.

Introduction

LiF:F_2^- color centers are highly stable at room temperature, withstanding high pumping intensities. These centers consist of a double vacancy configuration that shares three electrons. The main absorption band peaks, at 960 nm at room temperature, overlap the emission bands of Nd lasers fairly well, emitting in a broad band that peaks at 1.12 μm with a decay time[1] of 54 ns. These centers are produced by γ-ray irradiation and are one of the ultimate F aggregate products of irradiation.[2] Their properties as a gain medium have been reported for pulsed[3] and cw[4] operation. Because their long decay time, these crystals are used mostly for Q switching of Nd lasers; pulses as short as 5 ns can be produced in a simple way.[5] Simultaneous operation of the LiF:F_2^- absorber as a Q switcher and a laser medium in a longitudinal scheme was also reported.[6] As mode lockers, these centers have been used in three different situations:

(1) Mode locking of Nd:glass and Nd:YAG lasers by using a small initial absorption in long resonators has been reported[7]; the mechanism for these schemes is not completely understood since the modulation depth of the losses is due only partially to the long recovery time of the ground-state population during the round-trip time of the photons. In this case, the mode-locked pulses are produced randomly in such way that the modulation depth is not complete in every pulse.

(2) By using a combination of F_2^- and modified F_2^- color centers with a short decay time,[8] stable mode locking was obtained but with low energy efficiency.

(3) By using a coupled-cavity scheme in the transverse direction,[9] where obscillation of the F_2^- color centers is also achieved, simultaneous Q-switched and mode-locked pulses were obtained. However, because of the poor overlap of the two beams this scheme works only for high-power systems.

Experimental Arrangement

The sample used for our experiments was 3 cm long. The F_2^- centers in our sample had a decay time of 60 ns, with an optical density of 0.48 at 1.06 μm (internal transmission 40%). The Nd:YAG laser used in this experiment was homemade low-repetition-rate laser pumped by an air-cooled flash lamp in a tightly coupled pumping cavity, with an overall electrical-to-optical efficiency of ~1% in multimode operation.[10] The pump pulses, from a low-pressure xenon-arc lamp, were 120 μs long. For TEM_{00} operation a long-radius (10 m) mirror and a flat mirror were used, and the resonator was 180 cm long; two apertures

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were used, one ($\sim$2 mm in diameter) close to the curved mirror and the other ($\sim$1.2 mm in diameter) close to the plane mirror. The output coupler for the Nd laser is the flat mirror, with a transmission of $\sim$40% for 1.06 μm. An intermediate dychroic mirror was inserted close (6 cm away) to the output coupler. The mirror had a reflectance of less than 4% at 1.06 μm to avoid spurious oscillations and étalon effects that might prevent mode locking; it also had a reflection of more than 90% at 1.12 μm to minimize the oscillation theshold for the 1.12-μm laser emission and to permit its use as the output coupler. A schematic of the experimental arrangement is shown in figure 1. The initial alignment was done with the help of a dummy crystal of the same thickness carefully polished so it had the same wedge shape as that of the nonlinear element (this also prevented étalon effects). It should be mentioned that we did not observe oscillation at 1.32 μm in this resonator configuration. The round-trip time of the Nd laser is 12 ns; and the 1.12-μm cavity photon lifetime is at most 4 ns for this configuration.

Experimental Results

We observed first, that in our pumping conditions no oscillation was observed when only the back mirror and the intermediate mirror were used. By adjusting the front mirror so that the LiF:F_2^- crystal and the intermediate mirror were misaligned, we obtained Q-switched operation with pulses of typically 80-ns duration, with 5 mJ of energy in one pulse. This pulse duration is due primarily to the pumping rate that limits the growth of the field and the rate of saturation of the LiF:F_2^- crystals secondly to the long round-trip time of the Nd resonator, and thirdly to the slow recovery time of the saturable absorber. Careful adjustment of the intermediate mirror starts the LiF:F_2^- laser oscillation and provides a structure in the Nd pulses with the 12-ns round trip time of the Nd resonator. With the best alignment, full mode-locking structure is obtained. Figure 2 is an oscilloscope trace of these pulses. After these adjustments are made an easily reproducible and steady mode-locking temporal pattern could be seen in all pulses. This stability in the mode-locking regime remains as long as the two resonators are kept aligned. We have been using this crystal for the past 10 months, and its

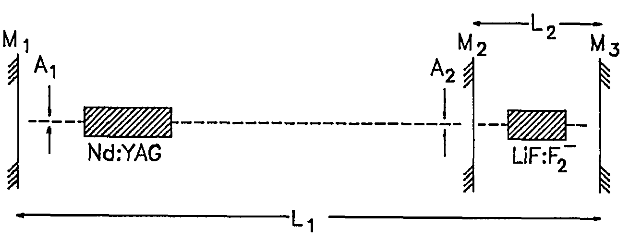

Fig. 1. Coupled-cavity laser scheme for the Nd:YAG and LiF:F_2^- laser media. The Nd:YAG laser resonator consists of mirrors M_1 (flat, output coupling 40%) and M_3 (10-m radius); apertures A_1 and A_2 are adjusted for TEM_{00} operation. Lens L_1 is 180 cm. The LiF:F_2^- resonator consists of mirrors M_2 (dychroic, output coupler) and M_3. Lens L_2 is 6 cm. M_3 is a highly reflecting broadband mirror.

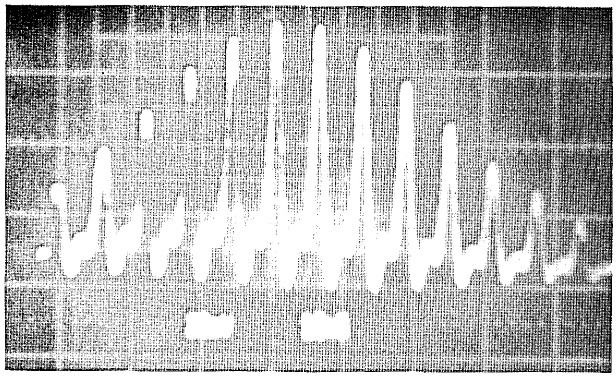

Fig. 2. Pulse train of the Nd:YAG laser when the LiF:F_2^- laser medium is also oscillating. The time base is 20 ns/cm. The pulses under the Q-switched envelope are 12 ns apart (round-trip time of the resonator).

performance with respect to the mode locking operation, has been practically unchanged. The pulse-envelope duration increased to 160 ns (FWHM), and the 1.06-μm envelope peak power decreased by approximately a factor of 10. Simultaneously, by using a prism outside the cavity we could observe the appearance of a second spot, much larger in size, that corresponds exactly to the expected dispersion of the prism for the 1.2 μm (SF3-type) prism. This spot was absent in the Q-switching case. This reduction in the envelope's peak energy is easily understood if we consider that there is a mechanism of energy transfer from the pump (1.06 μm) to the pumped laser (1.12 μm). The energy that is absorbed by the LiF:F_2^- crystal is due to the ground-state population, and this population is recovered faster because of the F_2^- stimulated emission (useful output power). In this case, the pulse duration is limited in the leading edge by the growth rate of the electromagnetic field in the F_2^- resonator and in the trailing edge by recovery time of the saturable absorber (laser medium), which depends on the intracavity energy density of the F_2^- laser medium according to $\tau_{\text{eff}} = \tau I_s/I$, where τ is the spontaneous decay time, I_s is the saturation intensity, and I is the intracavity intensity.

To estimate the average pulse duration, we used a background-free autocorrelator with a KDP crystal in type II orientation. The half-width of the second-harmonic intensity signal was approximately 300 ps. Thus we can estimate by deconvolution of the two interfering beams that the pulses are not longer than 200 ps. This result is conservative because the measurement is actually an average value; Fig. 2 shows clearly that the pulses at the wing of the Q-switched pulse envelope are longer than the central part because of the intensity dependence of this mechanism. It should be pointed out that the mode locking in this case is due not to the gain saturation of the Nd laser but to the gain saturation of the F_2^- color-center laser. In our case, the F_2^- effective decay time is of the order of a few nanoseconds, which is enough to force mode locking. One can conclude that an increase in the intracavity power density will decrease the pulse duration even further because of the pulse-shaping mechanism in this configuration.

In summary, we have shown that in a simple longitudinal coupled-cavity scheme it is possible to obtain complete mode locking of a Nd:YAG laser by using LiF:F_2^- color-center crystal as a passive Q switcher, mode locker, and active medium simultaneously. The train of pulses obtained is highly stable. In this configuration, laser action was obtained in both media, and the 1.06-μm mode-locked pulses obtained are due to the optimization of F_2^- cavity parameters. The conditions for energy exchange from the pump to the pumped laser are now under investigation.

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