Hybrid active and Kerr-lens mode locking of a diode-end-pumped Nd:YLF laser

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It is shown the generation of 6ps pulses from an acousto-optically modulated, Kerr-lens mode-locked, diode-end-pumped Nd:YLF laser. The average output power was 650mW. The laser spectrum in CW, as well as in mode locked operation, has shown inhomogeneous broadening due to the longitudinal spatial hole burning effect.

Demonstra-se a geração de pulsos de 6 ps a partir de um laser de Nd:YLF, bombeado longitudinalmente por diodo laser, com acoplamento de modos por modulação acusto-óptica e por lente Kerr. A potência de saída obtida foi 650 mW. O espectro do laser na operação CW, assim como no regime de acoplamento de modos, apresentou um alargamento inomogêneo devido ao efeito de "hole-burning" espacial longitudinal.

Introduction

Longitudinal pumping of Nd lasers is a powerful technique in order to attain high pumping rates and optical efficiencies, with the advantages of both improved stability and compactness. The majority of the end-pumped solid-state lasers, especially Nd-doped lasers, have as a common characteristic the proximity of the active medium with one end mirror. In these cases, strong effects of longitudinal spatial hole burning (SHB) causes the simultaneous oscillation of several longitudinal modes, that consists in an inhomogeneous broadening of the laser. This phenomenon can affect the mode-locking regime in a fundamental way [1,2,3]. The Kerr-lens mode locking (KLM) operation [4] of a diode-pumped Nd:YLF laser, demonstrated in the past few years [4,5], allows the generation of ultrashort pulses of the order of the gain-bandwidth limit (1 ps). In this paper, we demonstrate the generation of 6ps pulses from a hybrid, active and KLM, diode end-pumped, mode-locked Nd:YLF laser. It was verified, for the first time, a KLM regime with a gain broadening due to the SHB.

Experimental setup

For Kerr-lens mode-locking of diode-end-pumped Nd:YLF lasers, the minimum beamwaist obtainable from high power diode lasers, and the relatively low value of the Nd:YLF nonlinear index ($n_2 \cong 1.3 \times 10^{-16}$cm^2/W), are limiting factors that impose the use of an additional nonlinear medium in the cavity. Typically, it is used SF57 glass, that has a high value of n_2, 2.6×10^{-15}cm^2/W.

The laser cavity is shown in Figure 1. The π-oriented Nd:YLF crystal, cut at Brewster angle, had a Nd concentration of 0.6(1) mol% and length 13mm. The resonator was formed by two plane end mirrors, M_1 and M_2, and a set of two concave mirrors, M_3 and M_4, with 10cm radius, to produce an additional intracavity focus in the central arm of the resonator. At the center of this central arm a 1cm long sample of SF57 glass was inserted at Brewster angle. These two last mirrors were tilted at $\sim 15°$, in order to compensate for the astigmatism of the intracavity elements at Brewster angle. The Nd:YLF crystal was positioned close to mirror M_1, that has a high transmission for $\lambda_P = 797$ nm and is HR for the laser emission. M_3 was at 61.5cm from mirror M_1; M_4 was at 62cm from M_2. An acousto-optical modulator was also inserted in the cavity, close to mirror M_2, to provide an auxiliary amplitude modulation to sustain the mode-locking regime. The GaAlAs diode laser, used to pump the Nd:YLF crystal, delivers 4W of continuous power in a broad-area, at 797nm *(SDL-2382)*. The beam is collimated by a f=8mm objective and a 3x anamorphic prism pair. A 5-cm focal length lens then focused this beam into the Nd:YLF crystal. The measured spot dimensions of the pump beam (1/e radius of the field) were 60 × 300mm.

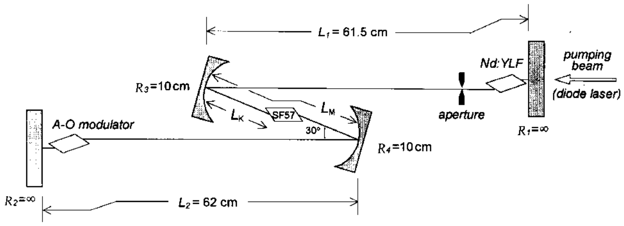

Figure 1. Experimental setup for the KLM of the diode-pumped Nd:YLF laser.

The central arm distance was adjusted to $L_M \cong$ 11.45cm, favoring the Kerr-lens sensitivity of the resonator [6], and providing a suitable beamwaist at mirror M_1 to have the best matching with the pumping beam. In this case, this beamwaist can be calculated as: $w_1 \cong 400\mu$m.

Experimental results

The system gain and loss parameters were determined as: $L \cong 0.2(1)$ and , $^0 \cong 1.2(4)$, where L is the linear cavity loss and , ^{0} is the unsaturated gain. The significant value for the intracavity loss, $L \cong 0.2(1)$, can be attributed to thermal lens aberrations in the gain medium caused by the asymmetric, rectangular-shape, pump beam. We have indeed observed strong beam distortions for CW pumping, relative to that for low duty cycle, pulsed pumping regime.

The background-free autocorrelation trace of the laser output in the CW regime (modulator off) has a bell-shape appearance, with a width of 20 ps (FWHM), and a background of 50% of the peak value, as shown in Figure 2-a. This is an expected result for low-coherence light, such as light due to a laser oscillating in a large number of independent modes [7]. If we consider the coherence time, τ_C, as of the order of the autocorrelation width, 20ps, the free-running bandwidth can be thus estimated as: $\Delta\nu = 1/\tau_C \approx 50$GHz.

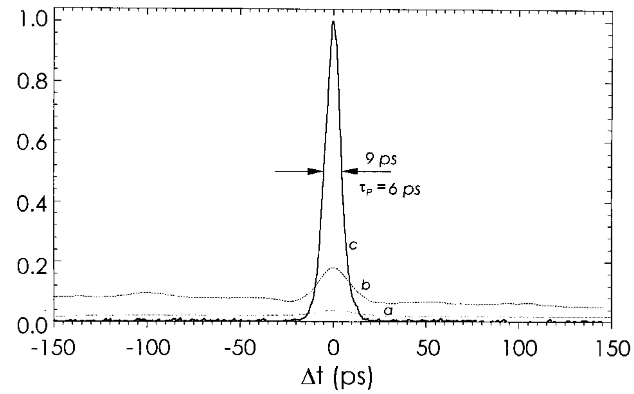

Figure 2. Autocorrelation curves for: a) CW regime (dotted curve), b) with d ≅0,03rad acousto-optic modulation (dashed curve), and c) KLM (solid curve).

When the acousto-optic modulator was adjusted for modulation depths above 0.6%, the laser became notably unstable, even for the best matching of the modulation frequency with the resonator repetition rate. This was probably due to the strong self- phase modulation (SPM) present in the system. However, when the acousto-optic modulation was reduced to the range $0.25\% > L_{AO} > 0.1\%$, the laser assumed a stable regime, with the same autocorrelation trace characteristics of the CW case, but with an amplitude 4 times higher (Figure 2-b). This indicates a regime with partial mode locking.

Finally, for an acousto-optic modulation of only 0.1%, and adjusting carefully the Kerr medium position, the modulation frequency (in a 10 Hz scale) and the laser alignment, we could observe the establishment of a complete mode-locking regime. In this case, the autocorrelation measurement has revealed a narrower trace, completely background-free, as shown in Figure 2-c. The critical dependence with the Kerr medium position, LK, clearly characterizes the KLM regime. We observed two intervals of the Kerr medium position that led to the KLM regime: 4.9cm$\leq L_K \leq$5.0cm and 5.3cm$\leq L_K \leq$5.4cm. It was also observed a critical dependence with the distance L_M, much narrower than the resonator stability interval, that is also expected in the case of KLM [6]. The resonator aperture was only due to the gain distribution in the active medium (moreover, due to thermal aberrations). The attempts to introduce a hard aperture close to mirror M_1 (see Figure 1) have resulted in deterioration of the regime. The KLM autocorrelation trace, Figure 2-c, has 8.8ps

FWHM, corresponding to an estimated pulsewidth of 6ps FWHM. This complete mode-locking regime was observed to be dependent on the acousto-optic modulation, so it was not possible to turn off the modulator. The output mirror transmission was 8% and the average output power was $P_{OUT} \cong$ 650mW. The amplitude noise on the second harmonic was around 10%, and the pulsewidth has shown variations of less than 5%, in repetitive measurements. The long-term stability was very good: more than 10h of continuous operation, without any change in the system characteristics.

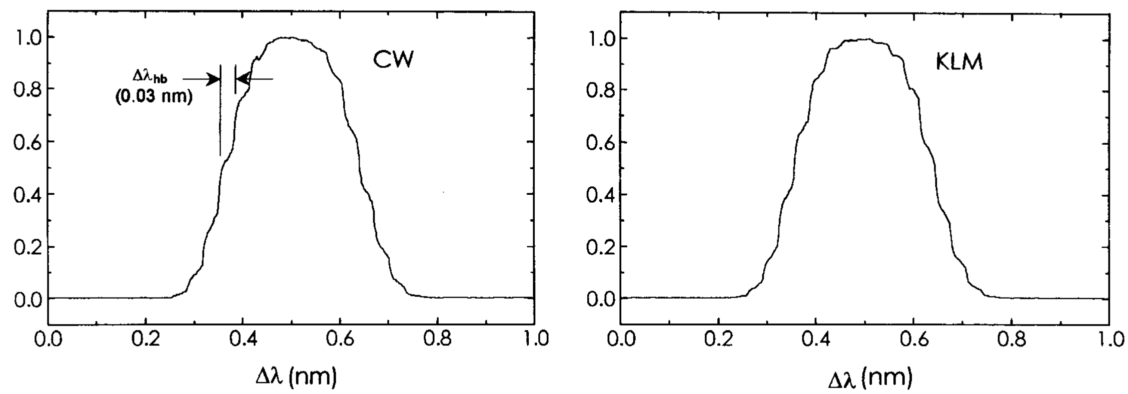

Figure 3. Time averaged laser output spectrum for both the CW and KLM cases showing the presence of hole burning modes.

The laser spectra, both in CW and in the KLM regime, coincide, as shown in Figure 3. Both spectra have full width at half maximum (FWHM) of approximately $\Delta\lambda \cong$ 0.3nm, $\Delta\nu \cong$90GHz, and its structure allows the identification of approximately 14 longitudinal modes of spatial hole burning (SHB), separated by $\Delta\lambda_{hb} \cong$ 0.03nm, $\Delta\nu_{hb} \cong$9GHz. Considering the following theoretical expression to the SHB modes, $\Delta\nu_{hb} \cong$ c/(4.d), where d is the effective separation distance between the active medium and the end mirror [8], we have $d \cong$ 8mm, very close to the actual mirror-Nd:YLF separation. It was used a 1m spectrometer *(SPEX)* with resolution in the order of 0.006 nm. Each complete measurement of the spectrum took approximately 10min to be performed, thus leading to a time averaged measurement. Due to this averaging, and to laser thermal drifts, it was not possible to visualize the individual SHB mode structure. The time-bandwidth product is $\Delta\nu\tau_P \cong$0.54, higher than the 0.31 expected for sech2 pulses, and 0.44, expected for Gaussian pulses.

Discussion

In our experiment, we verified that the weak active modulation was fundamental for the system stability. The best results of KLM in Nd lasers reported in the literature, regarding stability and self-starting behavior, always use some kind of phase-control [5,9]. The physical necessity of having an overall negative group delay dispersion (GDD) in the cavity, to achieve a steady-state KLM regime, is currently well understood. This is due the strong spectral modifications caused by the self-phase modulation effect (SPM) are intrinsic features of KLM schemes [10,11], and is especially important in the case of short bandwidth active media, like Nd:YLF. The absence of any GDD control in our experiment justifies the fundamental role of the weak active modulation for the establishment of the KLM regime.

Conclusion

In this work, a stable KLM regime with weak acousto-optic modulation could generate 6 ps pulses, with 650 mW of average power, in a diode-end-pumped Nd:YLF laser. This system has been operated continuously over more than 10 hours, without any change in its characteristics. It was verified that the well-known effect of longitudinal spatial hole burning (SHB), with enhanced magnitude in end-pumped systems, can be present during KLM operation of an end-pumped Nd:YLF laser. The SHB inhomogeneous broadening of the gain, and the lack of GDD control, have produced laser pulses with time-bandwidth product higher than that expected for the mode locking mechanism.

Acknowledgments

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