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Generation of intense 3 ps pulses by Kerr lens mode-locking of a pulsed Nd:YLF laser

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Abstract

We report on the generation of pulses as short as 3.1 ps from a flashlamp-pumped Nd:YLF laser by Kerr lens mode-locking with auxiliary active mode-locking and electrooptic feedback control. Long pulse trains and stable operation make this device well suited as a pump laser for pulsed operation of synchronously pumped dye lasers or optical parametric oscillators.

1. Introduction

Recently there has been considerable interest in developing new mode-locking techniques for solid-state lasers using intracavity nonlinearities. Especially the nonlinear refractive index was shown to be an effective and simple tool for the generation of stable and ultrashort pulses [1]. Pulses as short as 9 fs were reported recently for a Kerr lens mode-locked Ti:sapphire laser [2]. For a lamp-pumped cw Nd:YLF laser data on Kerr lens mode-locking were recently published: The authors also incorporated group delay dispersion in the cavity, yielding pulses of 2.3 ps and 5 nJ [3]. Similar results were obtained for Kerr lens mode-locked, diode pumped Nd-doped cw lasers by other investigators [4,5].

In this letter we demonstrate Kerr lens mode-locking of a flashlamp-pumped Nd:YLF oscillator generating ultrashort pulses of 3 ps and large output energy in the μJ range.

2. General

Some theoretical arguments on Kerr lenses will be presented first. Following Ref. [6] the intensity dependent lens effect of a Kerr medium in the laser cavity was evaluated for our experimental situation. The high intensity requirements of the nonlinear lens are fulfilled by a telescope with a beam waist in the Kerr medium. Using the *ABCD* formalism [7] the nonlinearity is described by the matrix **M**:

$$\mathbf{M} = \sqrt{1-\gamma}\begin{pmatrix} 1 & d_e \\ -\gamma/(1-\gamma)d_e & 1 \end{pmatrix}, \tag{1}$$

with $d_e = d_0/n_0$ effective length of the Kerr medium in the low intensity limit (refractive index n_0, length of the kerr medium d_0). The intensity dependence is described by the parameter γ:

$$\gamma = \left[1 + \frac{1}{4}\left(\frac{2\pi w_c^2}{\lambda d_e} - \frac{\lambda d_e}{2\pi w_0^2}\right)^2\right]^{-1} \frac{P}{P_c}, \tag{2}$$

where $P_c = c\epsilon_0\lambda^2/(2\pi n_2)$ represents the characteristic power of self-focusing. $w_c(z)$ and w_0 respectively denote the Gaussian beam radius at the entrance win-

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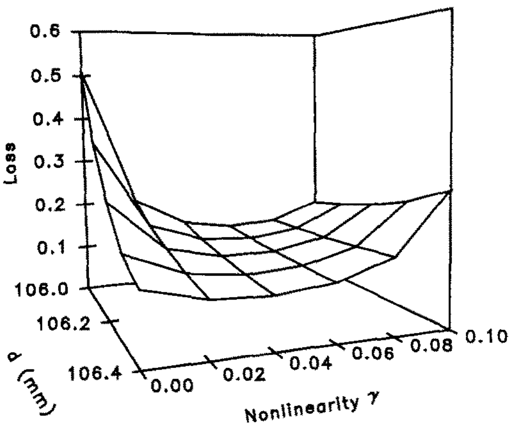

Fig. 1. Calculated data on Kerr lens mode-locking. The nonlinear loss is plotted versus the lens distance d of the telescope and nonlinearity γ; aperture radius $r_A = 1.0$ mm; details see text.

dow (position z) of the Kerr medium and the beam waist of the telescope. We notice here that a local effect is implicitly contained in Eq. (2), since the beam radius w_c depends on the position of the Kerr medium. Cavity parameters will be discussed below in context with the experimental setup.

The calculated loss through an aperture of radius 1mm is illustrated by Fig. 1, while the aperture is located 9 cm in front of the adjacent cavity mirror. The loss is shown as a function of the nonlinearity γ and different telescope distances d. The nonlinear medium in the telescope is positioned at $z = 62$ mm. One can clearly see that for smaller distances ($d \simeq 106.0$ mm) the loss through the aperture substantially decreases with increasing γ, i.e. for higher intensity. Starting from 50% loss per roundtrip this value reduces down to about 12% for optimum γ or intensity. For longer telescope distances ($d > 108$ mm) the opposite behaviour is computed. With increasing intensity inside the resonator the loss remains unchanged or even increases. For this situation no mode-locking effect by the Kerr lens setup is expected.

Fig. 1 illustrates the critical telescope alignment for Kerr lens mode-locking with a given position of the nonlinear medium. It is readily visualized from the figure that for proper alignment the peak of a pulse passing the KLM device may experience smaller reflexion losses than the pulse wings leading to pulse shaping and shortening. The magnitude of the effect depends on the slope of the loss curve.

3. Experimental

The resonator design is depicted schematically in Fig. 2. The cavity consists of two highly reflecting plane mirrors M1 and M2 and a telescope with two lenses L1 and L2. L2 is mounted on a translation stage enabling fine adjustment of the distance d between the two lenses L1 and L2. The distance between M1 and L1 is adjusted to 21 cm. In this short resonator arm the acousto-optic mode-locker AOM (modulation depth $\approx 50\%$) and the aperture A are placed. The former is helpful to initiate the passive mode-locking. The diameter of the aperture can be adjusted in the range of 0.3 and 10 mm with a precision of 0.1 mm. Nearby the focus of the telescope the nonlinear medium KM is placed (distance from L1: z), a 1 cm cuvette made of fused silica filled with CS_2 (spectroscopy grade). CS_2 displays a high Kerr nonlinearity and serves together with the adjustable aperture for Kerr lens mode-locking of the laser. The Kerr medium KM is also mounted on a translation stage.

The cylindrical laser rod LR is a Nd:YLF crystal with diameter of 4 mm. It is flashlamp-pumped with a repetition rate of 40 Hz and an electrical input energy of 32 J. The emission wavelength is chosen to be 1047 nm, because of the higher gain compared to the second laser wavelength at 1054 nm.

The amplitude of the circulating laser emission is controlled by variable losses accomplished by a pockels cell PC in combination with a polarizer P and a beam splitter BS directing part of the oscillator energy on a photodiode PD [8]. The polarizer P also serves as an output coupler of the resonator, providing approximately 50% of the circulating laser energy.

The length of the mode-locked pulse train varies between 5 and 25 μs (500 to 2500 pulses), depending on the aperture radius and position of the Kerr medium.

The pulse duration is measured by a standard autocorrelation setup applying a 0.2 mm thin KDP crystal while the spectra of the pulses are measured with an optical spectrum analyzer (OSA) and an $f = 0.5$ m monochromator.

4. Results

In the following we want to present the experimental results on the pulse duration as function of several

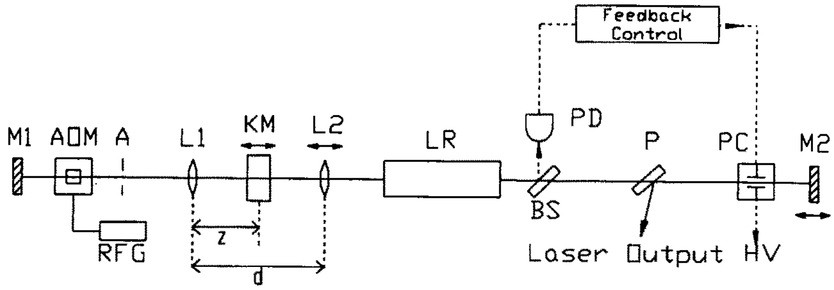

Fig. 2. Schematic of the pulsed laser system with Kerr lens mode-locking, electro-optic feedback control of the pulse amplitude and auxiliary active mode-locking; mirrors M1, M2 ($r = \infty$), telescope lenses L1, L2 ($f = 50$ mm); Kerr medium KM; acousto-optic modulator AOM; aperture A; laser rod LR; beam splitter BS; polarizer P; pockels cell PC; photodiode PD and electronic feedback control of the pulse energy.

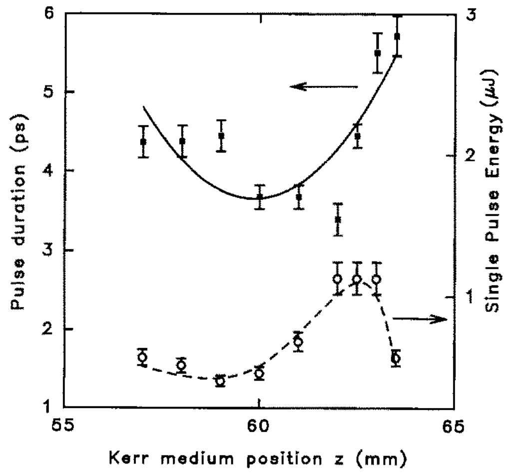

Fig. 3. Measured pulse duration (left hand scale, full squares) and single pulse output energy (right hand scale, open circles) versus position of the Kerr medium (1 cm of CS_2). Lines are drawn as a guide for the eye.

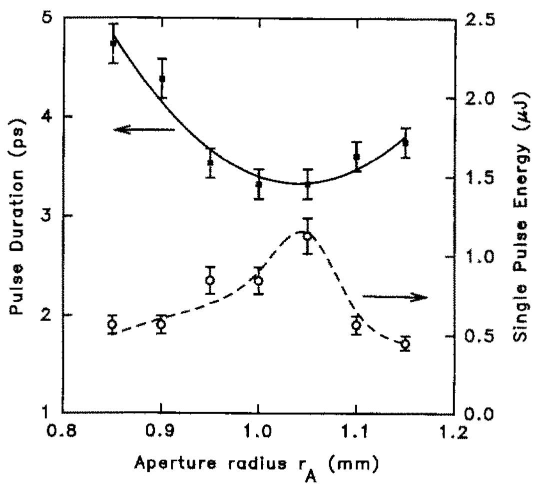

Fig. 4. Measured pulse duration (left hand scale, full squares) and single pulse output energy (right hand scale, open circles) versus aperture radius r_A; lines are drawn as a guide for the eye. The data demonstrate the KLM effect.

parameters influencing the Kerr lens mode-locking.

Fig 3. depicts the measured pulse duration (left hand scale, full squares) and output energy (right hand scale, open circles) versus position of the Kerr medium inside the telescope while the aperture radius $r_A = 1$ mm and the telescope distance $d \simeq 107$ mm are kept constant. Noteable changes of the pulse duration of 3.2 to 5.8 ps occur in the position range 57–63 mm. Outside this interval the laser worked in the purely active mode-locking regime (governed by the acousto-optic modulator). The observations demonstrate the critical effect of the position of the nonlinear lens in accordance with numerical investigations [9].

Of special interest is the variation of the single pulse energy on the position of the Kerr medium, although the amplitude level of the feedback control of the laser was not changed (open circles in Fig. 3). One can deduce two approximately stable levels of operation of 0.5 μJ and 1.2 μJ, while the amplitude level of the feedback control was adjusted to 1.3μJ. The pulse train length amounts to 8 μs and 5 μs, respectively. This self-stabilizing of a laser is well-known from additive pulse mode-locked lasers [10,11].

Fig. 4. shows the measured dependence of the pulse duration (left hand scale, full squares) and the single pulse output energy (right hand scale, open circles) on the radius of the aperture r_A for fixed position of the Kerr medium $z = 62$ mm and telescope distance $d \simeq 107$ mm. Minor changes of the pulse energy occur in the range $r_A = 0.85$ to 1.15 mm. Outside this small interval the laser was not passively mode-locked

due to the fixed pump power in this measurements: for larger aperture radii the smaller losses were not sufficient for passive mode-locking. Below r_A = 0.8 mm the laser did not reach its threshold. In dependence of the aperture radius the duration of the laser emission exhibits a clear minimum of 3.3 ps at $r_A \simeq 1$ mm. Deviations from this optimum value result in longer pulses up to 4.8 ps. The data clearly indicate Kerr lens mode-locking of the laser.

We have also investigated the pulse duration as a function of lens distance d of the telescope for fixed aperture radius r_A = 1 mm and KM position z = 61 mm. With increasing distance of the two lenses from d = 106.2 to 107.3 mm the duration of the laser pulses rises linearly from 3.5 ps to 6.4 ps. Outside the measured interval of d the laser resonator was not stable any more for the applied constant pump energy. The observed behaviour can be explained by the arguments presented above in context with Fig. 2. With shorter telescope distance d the Kerr lens mode-locking mechanism benefits from smaller losses of the peak of the laser pulse. A limit is set by the stability region of the cavity.

We have varied the nonlinearity of the Kerr medium by diluting CS_2 with benzene (smaller n_2 by a factor of 2.5), but dilution by only 10% already resulted in vanishing Kerr lens mode-locking.

The autocorrelation curve of the laser pulses for optimum alignment is depicted in Fig 5. The good agreement with a Gaussian shape is noteworthy. From the width of the measured curve a pulse duration of t_p = 3.1 ±0.2 ps (fwhm) is deduced, while the width of the Gaussian shaped spectrum is determined to 13 cm^{-1}. The bandwidth–pulse duration product amounts to $\simeq$ 1.2 suggesting a certain amount of chirp via selfphase modulation. Obviously a dispersion compensation in the laser resonator may lead to even shorter pulses. For example a Gires Tournois interferometer was applied in a cw Nd:YLF laser [3].

It is interesting to compare our pulsed Kerr lens mode-locked Nd:YLF laser with pulsed Nd:YLF lasers using a saturable absorber [12] or additive pulse mode-locking (APM) with a nonlinear Michelson interferometer [13] for passive mode-locking. The saturable absorber yields pulses of 7 ps at a higher energy level of 4 μJ, with shorter pulse train of about 150 pulses. The APM Nd:YLF system offers similar pulse parameters as the KLM laser discussed here:

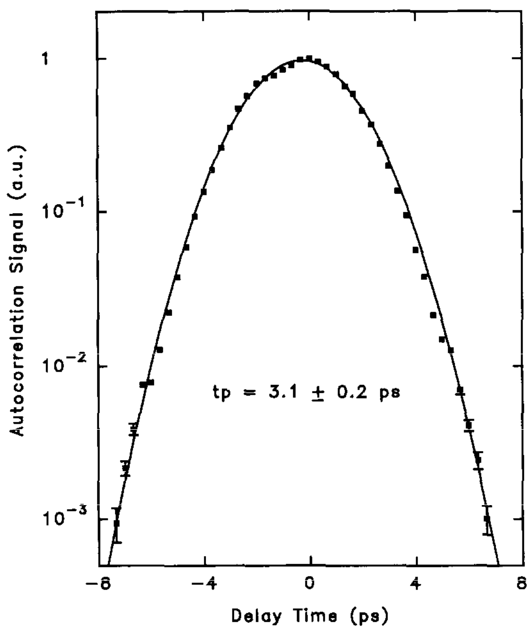

Fig. 5. Autocorrelation data for the Kerr lens mode-locked Nd:YLF laser with optimum alignment; a pulse duration of 3.1 ± 0.2 ps is measured assuming a Gaussian shape (experimental points, calculated Gaussian curve).

pulse durations of about 3 ps with single pulse energies of 0.5 μJ for longer pulse trains of ≈ 600 pulses. The APM laser however suffers from the need of an active stabilization of the length of the interferometer, which should be kept constant in the nm range.

The Kerr lens mode-locked Nd:YLF laser represents the simpler experimental approach without the need of active stabilization. Due to the use of a liquid Kerr medium the system is insensitive to nonlinear damage with excellent long term stability. In contrast to the APM laser the output energy is doubled and the reproducibility of the laser pulse energy of $\simeq$ 2% is improved.

The laser device is well suited as a pump source for synchronously pumped dye lasers [14] and optical parametric oscillators [15].

5. Conclusion

We have demonstrated Kerr lens mode-locking of a flashlamp-pumped, feedback controlled Nd:YLF laser generating 5 μs pulse trains with single pulses of 3.1 ps and output energy of 1 μJ. The reproducibility of the pulse amplitude of 2% and the increased output energy make the device well suited as a pump source for femtosecond optical parametric oscillators. Besides a simple experimental arrangement KLM leads to improved laser operation in comparison with APM.

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