Self-starting Kerr-lens mode-locked femtosecond Cr4+:YAG and picosecond Pr3+:YLF solid-state lasers

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Self-starting Kerr-lens mode-locked femtosecond Cr^{4+}:YAG and picosecond Pr^{3+}:YLF solid-state lasers

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We have observed true self-starting Kerr-lens mode locking in two distinct solid-state laser systems operating at room temperature by optimizing the cavity geometry to maximize the amplitude modulation with respect to the intracavity power variation. Pulses of 15 ps have been obtained from a Pr^{3+}:YLF laser system operating at 607 nm, and 53-fs pulses have been obtained from Cr^{4+}:YAG at 1.54 μm.

The discovery of self- (or Kerr-lens) mode locking[1] in Ti:sapphire has had a remarkable effect on the development of ultrashort-pulse laser sources, for which the emphasis is currently placed on solid-state lasers. The Kerr-lens mode-locking (KLM) mechanism mimics the behavior of a passive system incorporating an ultrafast absorber (with an effectively infinitely fast response time, that of the characteristic nonlinearity of the laser medium). The nonlinearity is the intensity-dependent refractive index, and the mode-locking mechanism has been explained in terms of an intensity-dependent gain–loss mechanism based on self-focusing as a result of the optical Kerr effect.[2] The mechanism has now become widely applicable to numerous solid-state laser materials, generating pulse durations from picosecond to femtosecond regimes, effectively limited by the gain bandwidth of the laser media, operating at wavelengths from the visible to the near infrared. Generally the nonlinear Kerr coefficients of the common solid-state laser materials are relatively small, and together with the low intracavity power fluctuations associated with typical cw pumping schemes, self-starting of the pulse formation is not commonly observed. Consequently, schemes have been devised to initiate and sustain the pulse formation mechanism. With Ti:sapphire lasers that use additional components, schemes have employed the implementation of saturable absorbers[3] or initiation through regenerative mode locking with an intracavity modulator.[4] True self-starting has also been observed by use of a unidirectional ring cavity configuration[5]; however, the required operational pump powers were relatively high. Similarly, self-starting was achieved by the introduction of an additional intracavity material with a high Kerr nonlinearity.[6] KLM has also been initiated through the production of a gain saturation lens,[7] but this techniques severely limits the wavelength of operation. It should, however, be noted that self-starting self-mode locking can be initiated by very low-loss modulation (i.e., $<10^{-5}$).

The most significant advance in the simplification of self-starting Kerr-lens mode-locked solid-state laser systems was recently reported by Cerullo *et al.*[8] and Magni *et al.*,[9] who demonstrated that through an optimized cavity geometry the fractional change of the cavity spot size with intracavity power variation could be maximized such that the intensity fluctuations of the cw laser could produce sufficient pulse shaping to lead to self-starting. The cavity configurations proposed and demonstrated contained no additional elements, enhancing the overall simplicity of the technique. In the research described here we report on the application of the technique of Cerullo *et al.*[8] and Magni *et al.*[9] to Cr^{4+}:YAG and Pr^{3+}:YLF lasers, for which the time scales of the intensity fluctuations are vastly different, generating femtosecond pulses in the infrared and picosecond pulses in the visible, respectively, from self-starting Kerr-lens mode-locked optimized cavity configurations.

With an upper-state lifetime of ~4 μs and a net gain cross section of 4×10^{-19} cm^2 the laser parameters of Cr^{4+}:YAG (Ref. 10) are close to those of Ti:sapphire, and similar performance should be expected over the room-temperature, cw lasing region 1.34–1.58 μm. This broad gain bandwidth is capable of supporting sub-100-fs pulses, and pulses in this regime have been reported by several groups of researchers who used KLM initiated by differing starting mechanisms.[11–13]

In the self-starting study described here, a standard four-mirror astigmatically compensated z-fold cavity was used. The 5-mm-diameter, 20-mm-long Brewster-angled cylindrical laser crystal was grown at the Polus Research and Development Institute, Moscow. At the pump wavelength of 1.06 μm this rod had an absorption coefficient of 1.1 cm^{-1}. The rod was indium clad and held in a copper housing, water cooled to a temperature of 15 °C. It was placed slightly off center between focusing mirrors of 100-mm radius of curvature. A plane-wedged output coupler of

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1% was used, and all the other mirrors were 100% reflecting. Two fused-quartz Brewster-cut prisms were included intracavity to permit group-velocity dispersion compensation. A cw Nd:YAG laser operating at 1.06 μm was used as the pump radiation, which was focused through one of the folded section cavity mirrors by a 100-mm focal-length lens, and a pump power coupling efficiency of 83% was achieved.

As a result of the noncompensatable perturbation to the group-velocity dispersion caused by intracavity water absorption[12] the operating wavelength of the laser was maintained above 1.5 μm, through the chosen reflection bandwidth of the mirrors. In cw operation, without the intracavity prism pair, 500-mW TEM_{00} output was obtained for a pump power of 7.5 W (threshold 1.2 W). On insertion of the prism pair, the output power reduced to 350 mW.

In obtaining self-starting KLM we made use of both hard and soft aperturing effects. The cavity was configured with almost equal arm lengths according to the formulation of Cerullo *et al.*[8] To optimize the effect of the soft aperture, initially the slit was omitted from the cavity. On adjusting and optimizing the separation of the folding mirrors and the position of the rod between these, we obtained a mode-locked signal. At this point, a vertical slit was introduced into the cavity and position and width adjusted to stabilize the mode locking. For optimum stability of the mode locking a 210-mm apex-to-apex separation of the prism pair was experimentally determined.

Figure 1 shows a background-free autocorrelation of 53-fs pulses (FWHM, assuming a sech^2 pulse shape) obtained from the self-starting Cr^{4+}:YAG laser. The corresponding spectrum centered at 1.54 μm had a bandwidth of 47 nm. This would imply an effectively transform-limited time–bandwidth product of 0.32. However, a cw component at 1.52 μm accompanied the mode-locked output, and this was always present in the outputs optimized for self-starting. The cw component contained less than 10% of the total output energy of the laser. It was possible to eliminate this component by reconfiguring the cavity. However, in this case the mode locking was not self-starting but required a mechanical perturbation; it was then stable in the long term.[12] The spectrum in the self-starting situation also exhibits evidence of the instability, i.e., noise and drop-out, which detracted from the applicability of this source.

Stable, self-starting mode locking was also obtained with the vertical slit placed before the output coupling and following the prism. In this case the slit operates to limit the bandwidth of the system, and stable 80-fs pulses were obtained. It was also observed with the self-starting configurations that cyclic breakup of the output pulse train occurred, in that the single pulse per round trip was prone to instantaneous breakup into two or three pulses, and a continuous movement of radiation shed from the pulse profiles was observed. This process bore some similarity to the pulse breakup and the random but periodic output often observed in femtosecond erbium-doped fiber lasers and is a consequence of the laser's operating in the spectral region of approximately zero group-velocity dispersion.

From our previous measurements, the dispersion of the simple four-mirror cavity at 1.54 μm was $+80\ \mathrm{fs}^2$. The overall cavity dispersion with the 210-mm apex–apex separation of the fused-quartz prisms taken into account was $-1867\ \mathrm{fs}^2$, assuming a total glass path of 4 mm. However, the third-order dispersion of the prism pair was determined to be $\sim 8103\ \mathrm{fs}^3$, and the total third-order dispersion of the cavity was more than $11{,}000\ \mathrm{fs}^3$. It therefore should be possible either by using prisms of low third-order dispersion or by compensating for the present component to generate substantially shorter output pulses.

We note that one important practical consideration in the self-starting Cr^{4+}:YAG laser is the role played by the thermal lens. For optimum performance the positioning of the pump lens is vital, and variations of 0.5 W in the pump power will terminate mode-locked operation. Self-starting of this laser system was always accompanied by a cw component and instability in the output, which may have arisen from the strong instability in the Nd:YAG pump source that was also present. These features made the present laser an impractical source, and greater reliability was obtained with the non-self-starting configuration.

As was recently reported,[14] the Pr^{3+}:YLF laser crystal permits considerable wavelength diversity and cw operation throughout the visible spectrum. Unfortunately the advantage of the wavelength selectivity of the reported lines is outweighed by the narrowness of these transitions, which can generally support pulses of only a few picoseconds. With both liquid and solid-state saturable absorbers, KLM has been instigated in this laser material, demonstrating picosecond pulse generation ($\sim$10 ps) in the 607- and 639-nm transitions.[15] In the research reported here, self-starting KLM of the $^3P_0$–$^3H_6$ (607-nm) transition is reported, once again based on the modulation optimization procedure of Cerullo *et al.*[8]

Figure 2 is a schematic of the cavity configuration employed. The Pr^{3+}:YLF crystal, which was grown at the Center for Research and Education in Optics and Lasers, University of Central Florida, was 9 mm long, 6 mm in diameter, and cut with Brewster-angled facets such that the electric field vector was perpen-

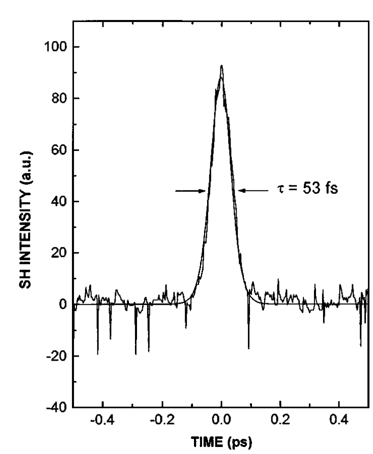

Fig. 1. Background-free intensity autocorrelation of 53-fs (assuming a sech^2 intensity profile) pulses from a self-starting Kerr-lens mode-locked Cr^{4+}:YAG laser. SH, second harmonic.

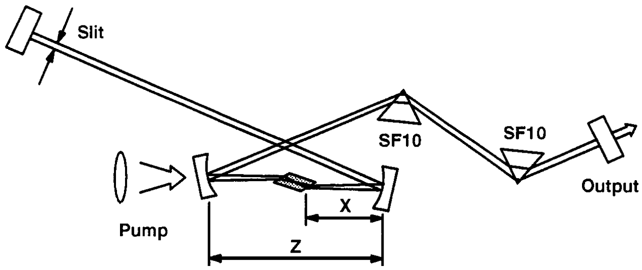

Fig. 2. Schematic of the cavity configuration used for the self-starting KLM of Pr:YLF. See text for notation.

dicular to the crystal *c* axis. The crystal was indium clad and held in a water-cooled copper jacket. The 0.8-at.% Pr^{3+}-doped crystal was pumped by the 476-nm line of an argon-ion laser, delivering as much as 3.4 W of power, of which at maximum 1.7 W was absorbed in the crystal. A standard *x*-fold cavity configuration was employed. An effectively symmetrical cavity was employed, with distances from the folding mirrors to the plane mirrors of 992 and 1014 mm. An intracavity slit (optimized width 2 mm) was also included to enhance the self-mode locking and was placed 15 mm from the plane high reflector. Dispersion compensation was employed with two SF10 prisms with an apex–apex separation of 439 mm. Self-starting was achieved with the optimization of the relative position of the crystal between parts of the folded section such that length x was 46 mm and the physical length of z was 1.07 mm. Typically, for the cavity arrangement shown in Fig. 2, the cw laser threshold was achieved for a pump power of 200 mW and self-mode-locking at 1.6 W. For an absorbed pump power of 1.7 W, 15 mW of mode-locked output (1%-output coupler) was obtained at 607 nm in pulses of 15-ps duration. It is interesting to note that for an equivalent-sized cavity, for which mode locking was initiated by a mechanical perturbation (tap starting), a single pulse per round trip was observed at ~70 MHz. Under the self-starting regime, period doubling was observed with a periodic pulse train at 140 MHz. This period doubling, which was also observed in the self-starting Cr^{4+}:YAG configuration, may arise from the fact that a symmetrical cavity arrangement is employed. In these bistable laser systems the active medium is placed approximately at the center of the cavity, mimicking a passively mode-locking colliding-pulse mode-locked laser with an ultrafast saturable absorber. In such a situation, i.e., with the saturable absorber at the center of the cavity, two-pulse operation and period doubling would generally be expected as the self-optimizing energy mode of operation of the system, as has been readily observed in dye lasers.

In summary, through maximizing the amplitude modulation with respect to the intracavity power through the optimum cavity geometry as described by Cerullo *et al.*,[8] we have demonstrated self-starting in two solid-state lasers that incorporate no additional cavity elements in relatively simple configurations. These two lasers operated in distinct temporal regimes. However, greater stability appeared to be achieved in configurations when the mode locking was not self-starting but initiated through a mechanical perturbation. In self-starting operation the Pr:YLF laser generated pulses of 15 ps and average powers of 15 mW at 607 nm. As much as 250 mW of power was obtained from the Cr:YAG laser system, which generated pulses as short as 53 fs. Combined with diode pumping, self-starting KLM provides a means to develop reliable, low-cost ultrafast lasers with no compromise of tunability such as occurs with systems initiated with resonant saturable absorbers. Since the initial submission of this manuscript (July 1995), we have demonstrated, using a mini Nd:YAG pumping scheme, highly stable, self-starting KLM in Cr^{4+}:YAG with pulse durations of <70 fs.

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