Self-mode locking of a diode-pumped Nd:YLF laser

G. P. A. Malcolm and A. I. Ferguson

Department of Physics and Applied Physics, University of Strathclyde, Glasgow G4 0NG, UK

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We report on the self-mode locking of a diode-laser-pumped Nd:YLF laser. Pulses of 6-ps duration have been obtained by using only a glass rod placed at an intracavity focus and an aperturing slit near the output coupler to achieve pulse shaping. The mode-locking mechanism is believed to be that of self-focusing (Kerr lens mode locking) owing to the optical Kerr effect in the glass rod. The pulses are approximately bandwidth limited, and the process can be self-started by a mechanical perturbation to the system.

Recently there has been a revival of interest in the development of mode-locked solid-state lasers. Novel passive techniques of mode locking based on nonlinear pulse shaping have been developed in color-center, Ti:sapphire, Nd:YAG, Nd:YLF, and Nd:glass lasers.[1-7] In many instances these mode-locking schemes have been shown to self-start and can produce the shortest reported pulse widths for each gain medium.

Ti:sapphire has proved an important and interesting laser system for investigation of these new ultrashort-pulse generation techniques, owing to its extremely broad gain bandwidth and high intracavity and output powers. A novel self-mode-locking technique was recently reported for a Ti:sapphire laser based on a single misaligned cavity configuration operating in multiple transverse modes.[8] The use of an intracavity aperturing slit has been shown to extend this form of mode locking so that no misalignment of the cavity is necessary.[9,10] This technique of self-mode locking has been proposed to be due to a Kerr self-focusing effect[11] in the gain medium and has been termed Kerr lens mode locking. A self-focusing microdot mirror and Kerr polarization modulator also produce self-mode locking but utilize the nonlinearity of an additional intracavity element other than the gain medium.[12]

Diode-pumped all-solid-state (holosteric) lasers have achieved unprecedented efficiency and compactness. The use of the highly stable diode laser also offers great advantages over the traditional flash lamp as a pump source for mode-locked solid-state lasers, including shorter pulse durations and superior stability. Active mode locking of diode-pumped Nd:YAG, Nd:YLF, and Nd:glass lasers with the use of amplitude- and phase-modulation techniques have been widely reported and have produced pulses of 7–10 ps.[13-21] More recently the passive self-starting technique of additive-pulse or coupled-cavity mode locking has been demonstrated to produce pulses as short as 1.5 ps in diode-pumped Nd:YAG and Nd:YLF lasers.[22,23] These systems, however, require that a significant portion of the diode-pumped laser output be directed into a coupled cavity containing a single-mode optical fiber to achieve pulse shaping, thus significantly reducing the output available from such lasers. An added complication in these systems is that they also require interferometric stabilization. Coupled-cavity resonant passive mode locking of a diode-pumped Nd:YLF laser that uses a multiple quantum well in a coupled cavity produces pulses as short as 4 ps.[7]

In this Letter we report on what is to our knowledge the first demonstration of self-mode locking of a diode-pumped Nd:YLF laser using the technique of Kerr lens mode locking to produce, in a completely passive manner, pulses of 6-ps duration. Nd:YLF is an attractive medium for a mode-locked diode-pumped laser as it offers high efficiency combined with a relatively large gain bandwidth, more than twice that of Nd:YAG, therefore yielding shorter pulses.

Kerr lens mode locking has been proposed to cause mode locking by a self-focusing action equivalent to that of a fast saturable absorber.[11] Experimentally this is achieved by introducing a variable aperture at a position in the cavity where the mode size decreases for increased intensity because of the Kerr lensing medium. This creates an intensity-dependent loss mechanism used to drive mode locking. This technique is not self-starting but can be initiated by a strong perturbation to the free-running laser.

The technique of self-mode locking of a diode-pumped Nd:YLF laser represents a simple and convenient method of producing a compact picosecond source without the requirement for intracavity modulators and associated rf generator and amplifiers, although these were used for alignment purposes in these experiments. Because all-optical modulation and pulse shaping are used to achieve mode locking in this scheme, the laser is also self-stabilizing, therefore no interferometric matching of cavity lengths is required, as in the case of coupled-cavity mode locking.

A schematic diagram of the self-mode-locked diode-pumped Nd:YLF laser is shown in Fig. 1. The cavity was based on an astigmatically compensated folded cavity of the type that has become common for diode-pumped lasers, with two additional mirrors to form an auxiliary intracavity focus. The pump lasers were 3-W GaAlAs diode-laser arrays

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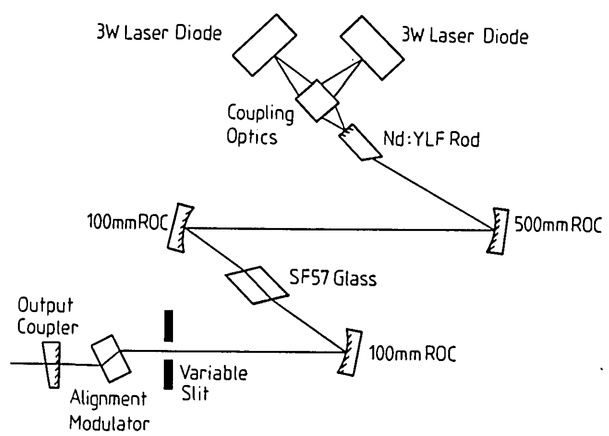

Fig. 1. Schematic diagram of the self-mode-locked diode-pumped Nd:YLF laser. The modulator is used only as an aid during the initial alignment and plays no role in the self-mode-locking process.

(Spectra Diode Laboratories SDL2482-P1) that were wavelength selected and temperature controlled for operation near 792 nm, the peak of the absorption of Nd:YLF. Two 6.5-mm focal-length lenses with high numerical aperture focused the output of the diodes in their highly divergent planes. The polarization of one diode was rotated through 90° by using a half-wave plate, so that the two orthogonally polarized beams were coupled with a polarizing beam splitter. The beam was focused in the other plane by using a combination of two 40-mm cylindrical lenses placed before the beam splitter and a 10-mm cylindrical lens placed before the Nd:YLF rod. This arrangement produces a focus on the laser rod of approximately 270 μm. The Nd:YLF rod was plane–Brewster cut for operation on the 1.047-μm high-gain line of Nd:YLF. The plane end was coated to be highly reflecting at 1.047 μm and antireflecting at 792 nm. The cavity was completed by a 500-mm radius-of-curvature (ROC) folding mirror, two 100-mm ROC mirrors that provided an intracavity focus, and a plane output coupler of 2% transmission with a 2° wedge on its rear surface.

Longitudinal end-pumping schemes for diode-pumped solid-state lasers of the type employed in the diode-pumped Nd:YLF laser are efficient. The minimum focused spot from a high-power diode laser array requires that the laser mode size in the gain medium of the diode-pumped system be fairly large, typically in excess of 100 μm, to ensure high efficiency. The nonlinearity produced in the gain medium is therefore too small to achieve self-mode locking of the diode-pumped laser. Instead a rod of glass placed at a tight intracavity focus provides the necessary nonlinearity. The glass used was a 1-cm Brewster-angled rod of SF57 placed at an intracavity focus of approximately 30 μm. The intracavity focus was located near the midpoint of the folded arm of the diode-pumped laser. A variable-aperture slit was placed near the output coupler to complete the scheme for self-mode locking. This position was chosen because simple Gaussian beam calculations indicate that a weak lens placed asymmetrically between the focus mirrors gives rise to a reduction in spot size at the beam waist on the output coupler. The slit therefore creates a lower cavity loss for high intensities as self-focusing occurs and favors mode-locked operation over cw operation.

In these initial experiments an acousto-optic modulator was placed in the cavity to aid alignment of the self-mode-locked laser. The cavity repetition rate was set to 122 MHz, and the laser produced pulses of ~100 ps when acousto-optically mode locked, owing to the small modulation index of the modulator. The cavity was aligned for maximum output power with the slit completely open. Careful adjustment of the separation of the mirrors around the SF57 glass and the position and size of the aperture produced short pulses from the system. These pulses shortened suddenly to establish self-mode locking, and, provided that the system continued to self-mode lock, adjustment to the slit width or mirror position did not significantly alter the pulse duration. The modulator was then turned off, and mode locking was sustained. Indeed once the system is aligned and the aperture set, mode locking can be initiated simply by a mechanical perturbation of the system, for example, by tapping one of the mirror mounts. Once started the mode locking was sustained until the laser cavity was blocked. The laser then ran in the cw mode when the cavity was unblocked. Occasionally spontaneous self-starting could also be observed. The aperture was seen to impinge slightly on the laser mode in the cavity when it was adjusted for self-mode locking. With the cavity mirrors adjusted to achieve self-mode locking the laser ran on a low-order multiple transverse mode. Several different modes were observed in which self-mode locking could be achieved including a near TEM_{00} central spot with additional higher-order sidelobes. Whether operation in a higher-order mode is crucial for self-mode-locked operation or whether multimode operation was due to the parameters required to achieve self-mode locking in this laser, resulting in poor mode matching in the Nd:YLF rod, is currently under investigation.

The self-mode-locked laser displayed excellent stability, with amplitude noise of less than 1% (rms from dc to 10 kHz) autocorrelations did not drift

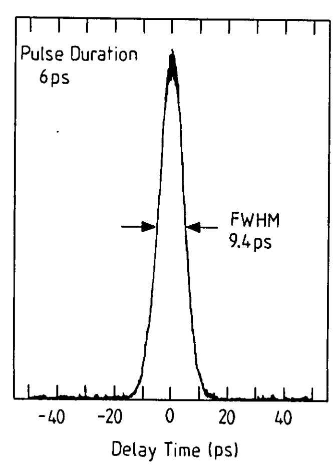

Fig. 2. Typical background-free autocorrelation of pulse of 9.4-ps FWHM, which corresponds to a pulse duration of 6 ps if a $sech^2$ pulse shape is assumed.

with time, and the amplitude noise on the second harmonic was 4%, which indicated both good long- and short-term stability of the pulse duration.

The output power for both cw and mode-locked operation of the Nd:YLF laser was 80 mW, for an incident pump power of ~5 W upon the Nd:YLF rod, compared with 100 mW with the slit completely open. This pump power could be reduced to 4 W, with little change in duration of the pulses before the system suddenly stopped mode locking.

Figure 2 shows a typical background-free real-time autocorrelation from the self-mode-locked Nd:YLF laser. The pulses were of 6-ps duration assuming a sech^2 pulse shape and had a time-averaged bandwidth of 55 GHz, measured with a grating spectrometer. This spectrum showed no indication of cw radiation as has been observed in some experiments on self-mode-locked Ti:sapphire lasers. This gives a time–bandwidth product of 0.33, which indicates that the pulses are bandwidth limited. Ti:sapphire lasers mode locked by this technique but without dispersion compensation, however, produce highly chirped pulses. The Nd:YLF laser may produce pulses at the transform limit owing to the much narrower bandwidth of Nd:YLF, a significant portion of which is required to sustain the short pulses, or owing to compensation of the group-velocity dispersion by the cavity mirrors or Brewster surfaces. The addition of dispersion-compensating prisms will allow further investigation of this behavior.

Many improvements are possible for the self-mode-locked diode-pumped Nd:YLF laser, which promise to improve the usable output and pulse duration from this type of laser. This system is at present rather inefficient as it yields only 80 mW of power, corresponding to a slope efficiency of 1.6%. This inefficiency is due mainly to the use of a 2% output coupler to achieve a sufficiently high intracavity power for self-mode locking to occur. Optimization of the nonlinear medium to permit increased output coupling (15% output coupling is optimum for the cw Nd:YLF laser) will improve the efficiency. The cavity design also requires optimization to achieve the correct focusing in the nonlinear element and good mode matching between the pump beam and the laser mode, which should also increase efficiency. The addition of intracavity dispersion compensation[24] may yield even shorter pulse durations by operating the cavity with a net negative dispersion and therefore allowing solitonlike pulse formation.[9]

In conclusion, we have reported the first demonstration to our knowledge of a self-mode-locked diode-pumped Nd:YLF laser. In these preliminary results we have observed 6-ps, bandwidth-limited pulses. A nonlinear element, in this case SF57 glass, placed at an intracavity focus and an intracavity slit are the only elements required for self-mode locking the diode-pumped Nd:YLF laser. This technique requires further investigation to optimize the pulse duration and output power but promises to be an important and widely applicable method of short-pulse generation from diode-pumped lasers.

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Note added in proof: Improvement of mode matching in the Nd:YLF rod and the use of a 10% output coupler have resulted in an output of 1 W in 6-ps pulses from the self-mode-locked diode-pumped Nd:YLF laser in a completely passive manner (modulator removed).

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