Self-starting additive-pulse mode-locked diode-pumped Nd:YAG laser

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A diode-pumped Nd:YAG laser is demonstrated by using self-starting additive-pulse mode locking with a nonlinear external cavity. Pulse durations of 1.7 psec are generated at an average output power of 25 mW without the need for active amplitude or phase modulation. Design and scaling issues for this technology are discussed.

Diode pumping has emerged as an efficient and compact method for pumping solid-state lasers. Numerous approaches have been demonstrated with both single and multiple diode-pump arrays to achieve high-efficiency operation in Nd:YAG, Nd:YLF, and other materials.[1] Active mode locking by amplitude or phase modulation has been demonstrated in diode-pumped Nd:glass, Nd:YAG, and Nd:YLF.[2–6] Pulse durations as short as 7 psec have been achieved.[5]

Recent studies have shown that a nonlinear external cavity can be used to enhance the pulse-shortening and mode-locking performance in actively mode-locked color-center lasers[7–12] and in Ti:Al_2O_3.[13] This technique has been termed additive-pulse mode locking (APM) because the pulse-shaping mechanism depends on the coherent addition of pulses that are fed back from the external cavity to pulses in the main laser cavity.[11,14] In the pulsed Nd:YAG laser, other techniques have been demonstrated for mode locking by using second-harmonic generation in an external cavity.[15,16]

The APM technique was recently extended to achieve self-starting, passive APM in a tunable Ti:Al_2O_3 laser.[17] The significance of self-starting APM is that ultrashort pulses can be generated without the need for active external amplitude or phase modulation, thus resulting in a significant reduction in the laser system cost and complexity. These studies suggest that self-starting can also be achieved in other laser systems that have properties comparable with those of Ti:Al_2O_3. Recently a theoretical criterion for self-starting was formulated that identifies gain cross section as an important parameter in determining whether self-starting APM is possible.[18] The research reported in this Letter, as well as concurrent research by other investigators demonstrating self-starting in a discharge-pumped Nd:YAG laser, establishes the generalizability of self-starting APM to other solid-state laser systems.[19]

In this Letter we demonstrate picosecond pulse generation in a diode-pumped Nd:YAG laser by using self-starting APM. Passive mode locking is achieved without the need for external amplitude or phase modulation. A stable train of 1.7-psec pulses is produced with an average output power of 25 mW. To our knowledge, these are the shortest pulses generated in a mode-locked Nd^{3+} laser to date. These results demonstrate the feasibility of self-starting APM for ultrashort-pulse, diode-pumped solid-state lasers.

Figure 1 is a schematic diagram of the mode-locked diode-pumped Nd:YAG laser. The laser uses a novel diode-pumping scheme that matches the pump spot size to the laser mode by combining beams to achieve a more symmetric aperture filling.[20] The Nd:YAG laser was pumped with three 0.5-W diode arrays that were temperature controlled to tune their emission wavelength to the Nd:YAG absorption band at 809 nm. Each laser array output was collimated, and the resulting beams were stacked in the dimension in which they were diffraction limited. By using a pair of orthogonal cylindrical lenses, the beams were focused into a 4-mm-long, antireflection-coated Nd:YAG crystal.

The Nd:YAG main laser cavity consisted of a dichroic flat end mirror with high reflectivity at 1.064 μm and high transmission at 810 nm, a spherical turning mirror (r = 60 cm), and a flat 14% transmitting mirror, which functioned as the output coupler. Without the external cavity, the Nd:YAG laser had a threshold of 630-mW diode pump power and produced a maximum continuous-wave output of 250 mW at 1.1-

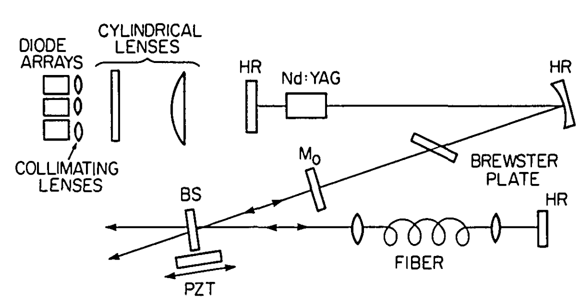

Fig. 1. Schematic of the diode-pumped Nd:YAG laser. Three diode arrays are used as the pump source. The main laser cavity is formed by the highly reflecting end mirror, the curved folding mirror (r = 60 cm), and output coupler M_0. The external cavity consists of a beam splitter, an optical fiber, and a retroreflecting mirror. HR's, high-reflectivity mirrors.

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W pump power. Mirror separations were adjusted to produce stable operation, with an overall optical length of 1.1 m corresponding to a round-trip frequency of 136 MHz. The laser emission was polarized by a Brewster window placed inside the main laser cavity.

The external coupled cavity was formed by a beam splitter (BS), an optical fiber, and a retroreflecting mirror. Measurements were performed with beam-splitter reflectivities of 90% or 70%. The light reflected from the beam splitter was collimated with a 17-cm best-form lens before being coupled into a single-mode optical fiber. In order to reduce stray reflections, which would interfere with the self-starting mode-locking process, the incident beam was coupled into the fiber, using a graded-index lens (0.23 pitch) that was antireflection coated on one side and coupled to the fiber with index-matching fluid on the other side. the fiber was single mode and had a core diameter of 7 μm. The typical coupling efficiency to the fiber was ~80%. An identical optical arrangement was used to couple out of the end of the fiber, and the resulting beam was retroreflected back through the fiber.

Two fiber lengths, 83 and 155 cm, were used for these measurements. For a given fiber length, the time of flight of a pulse in the external cavity was adjusted to be an integral multiple of the main laser cavity. This ensured that pulses that were reinjected from the external cavity would be synchronized with pulses in the main cavity. A piezoelectric translator (PZT) attached to one of the mirrors in the external cavity provided fine adjustment of the relative cavity lengths.

The nonlinearity of the fiber in the external cavity produces an intensity-dependent feedback to the main laser. The interference of the fields in the main laser and the external cavity produces a round-trip phase-dependent reflectivity, while the nonlinear index of refraction in the fiber causes this reflectivity to be intensity dependent.[11] Depending on the relative cavity length settings, the external cavity can function as a fast saturable absorber or a saturable gain. Alternatively, the laser can be viewed as incorporating an all-optical switch in the form of a nonlinear Fabry–Perot resonator that produces the pulse shaping and mode locking.

The choice of the laser cavity parameters, including output mirror transmission, beam-splitter reflectivity, cavity length setting (phase), fiber length, and intensity in the fiber, is important for optimization of the self-starting APM behavior since the parameters control the magnitude of the nonlinearity. Although the 14% output coupler used was not optimal for a continuous amplitude laser, the high coupler transmission is essential for the self-starting APM Nd:YAG laser. Higher output coupler transmission enhances the nonlinear reflectivity of the external cavity.

The output coupler, the beam splitter, and the fiber coupling efficiency determine the Q value of the external cavity. A high-reflectivity beam splitter reduces the available output power but produces a high-Q external cavity that has enhanced nonlinearity and a rapidly varying effective reflectivity as a function of round-trip phase difference between the two cavities. A high-Q cavity enhances the self-starting behavior but is highly sensitive to relative cavity length settings. Conversely, a lower-reflectivity beam splitter produces more output power but results in a lower-Q external cavity that tends to reduce self-starting yet has a less phase-sensitive operation.

The choice of fiber length and intensity coupled into the fiber also controls the nonlinear phase shift that is produced on the field in the external cavity. This in turn controls the magnitude of the intensity-dependent reflectivity. The nonlinear phase shift scales as the product $n_2 I L_f$, where n_2 is the nonlinear index of refraction of the fiber, I is the intensity in the fiber, and L_f is the fiber length. Although n_2 is small, the intensity and fiber length can be scaled in order to enhance self-starting. It is important to note that the external cavity length can be set to an integer multiple of the main laser cavity length so that fiber lengths can be made significantly longer than the main laser.

Self-starting APM was achieved for a range of external cavity parameters. The shortest pulses were obtained by using a beam splitter of 90% and a fiber length of 83 cm with an external cavity length that was twice the main cavity length. The power coupled into the fiber (single pass) was 100 mW, and the system output power was 25 mW. The threshold for self-starting was approximately 80 mW of power coupled into the fiber. By appropriately adjusting the external cavity length, stable trains of pulses were generated. Figure 2 shows a background-free, second-harmonic-generation (SHG) autocorrelation trace of the pulse. The pulse duration is 1.7 psec FWHM if we assume a sech^2 pulse shape. The spectrum of the pulse was measured with a grating spectrometer and an optical multichannel analyzer. The FWHM of the spectral bandwidth was ~0.67 nm. Thus the pulses had a time–bandwidth product of ~0.30 and were nearly transform limited.

In the limit of low dispersion, self-starting APM is analogous to fast saturable absorber mode locking. For saturable absorber mode locking, the pulse width is inversely proportional to the gain bandwidth rather than inversely proportional to the square root of the gain bandwidth as in active mode locking.[21] Consequently, much shorter pulses are realizable in the APM system than for active mode locking. Even

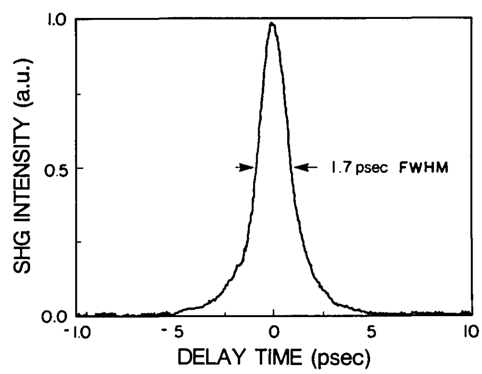

Fig. 2. Autocorrelation of self-starting additive-pulse mode-locked laser output. The pulse duration is 1.7 psec if we assume a sech^2 pulse shape.

shorter pulse durations can be anticipated in Nd:YLF or Nd:glass, in which the gain bandwidth is broader.

Scaling of operating parameters can be made in order to evaluate design trade-offs among self-starting, output power, and pulse duration. An increase in the fiber length from 83 to 155 cm approximately doubles the nonlinear phase change at a given intensity. With a beam splitter of 90%, the threshold for self-starting was reduced from 80 mW of power in the shorter fiber to 35 mW of power in the longer fiber. The increased nonlinear phase shift from the increased fiber length can also be traded against the Q of the external cavity and the laser output power. A decrease in the beam splitter to 70% resulted in a self-starting threshold of 85 mW, which was comparable with the value obtained by using an 83-cm fiber with a 90% beam splitter. Operation at full power produced a 60-mW output compared with 25 mW for the 70% beam splitter case. However, the pulse width for the longer fiber increased to 2.3 psec. It should also be possible to increase the output power by decreasing the loss other than the beam-splitter transmission in the external cavity. Optimization of the main laser cavity should also yield increased output with lower diode-pump requirements.

These results demonstrate the scalability of the system. It is anticipated that lower-power diode-laser-pumped sources can be mode locked at the expense of increased pulse duration by increasing the fiber length. It is important to note that the optical fiber nonlinearity is extremely fast, and thus the pulse repetition rate is not limited by external modulation as it is in active mode locking. Thus extremely compact and high-repetition-rate diode-pumped systems can be constructed by decreasing the main cavity length while maintaining longer fiber lengths to preserve the net nonlinear phase shift and the self-starting mode locking.

Although stable mode-locked pulse trains were generated from the system, if the relative cavity lengths were not maintained at the correct phase, or if stray reflections were present the system was also prone to self-Q-switching or relaxation oscillations. This situation is in contrast to self-starting APM in $Ti{:}Al_2O_3$, in which these instabilities are not observed.[17] While $Ti{:}Al_2O_3$ has an upper-state lifetime of $\sim 3\ \mu sec$, the lifetime in Nd:YAG is $\sim 240\ \mu sec$. Thus relaxation oscillations are damped more slowly, so instabilities are more likely in Nd:YAG as well as in other systems with long lifetimes such as Nd:YLF and Nd:glass. A rate-equation analysis has been recently performed to establish criteria for relaxation-oscillation instability.[19] In the diode-pumped Nd:YAG, the relaxation-oscillation instabilities can produce periodic spiking of 1–2-μsec duration at the relaxation-oscillation frequency of 35 kHz. Transitions between stable mode locking and relaxation oscillations as well as a superposition between these two states can be observed depending on the laser's operating parameters.

In summary, we have demonstrated picosecond pulse generation in a diode-pumped Nd:YAG laser using self-starting APM. Pulse durations as short as 1.7 psec have been achieved. We believe that these are the shortest pulses generated in a mode-locked Nd^{3+} laser to date. Approaches for scaling in power and repetition rate have been outlined. We believe that the combination of diode-laser pumping of solid-state materials and self-starting APM holds promise of the development of a compact and versatile ultrashort-pulse technology.

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