True fundamental solitons in a passively mode-locked short-cavity Cr^{4+}:YAG laser

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We demonstrate a self-starting, passively mode-locked short-cavity Cr^{4+}:YAG laser that supports fundamental intracavity solitons over wide ranges of cavity group-velocity dispersion and pulse energies. The total dispersion and nonlinear effects are small enough that stable, $N = 1$ soliton pulses are generated. Equally spaced multiple pulsing is also observed, with fundamental soliton behavior preserved. Regions of bistability exist where, at a constant cavity dispersion, the laser can produce transform-limited pulses of a different width and energy. The laser produces 200-fs pulses at approximately 0.9-, 1.8-, and 2.7-GHz repetition rates with a total of 82 mW of average output power. © 1997 Optical Society of America

The well-known solution to the nonlinear Schrödinger equation for the stable propagation of an optical pulse in the presence of nonlinear self-phase modulation (SPM) and group-velocity dispersion (GVD) is the soliton that arises from a stable balance between the SPM and the GVD in both sign and magnitude. In a mode-locked laser both GVD and SPM are present in the cavity elements, causing perturbations in the temporal shape and optical spectrum of the pulse as it propagates through the cavity. For stable mode-locked operation, all perturbations to the pulse from individual cavity elements must counteract one another such that the pulse experiences no net change with each complete cycle through the cavity.[1] For soliton propagation in a laser cavity the pulse must be a soliton relative to the average GVD and SPM, and all perturbations to the pulse from GVD and SPM must remain small. Although this balance between GVD and SPM is widely present in mode-locked cavities, the amount of GVD and SPM is frequently large, causing substantial deviations of the temporal shape and spectrum such that the pulse does not react as a soliton.

In this Letter we present a novel mode-locked laser for which an extremely compact cavity (900 MHz) leads to low pulse energies (for a constant cavity energy, the pulse energy scales inversely with repetition rate) and thereby to reduced SPM. Furthermore, the intracavity elements individually exhibit low GVD. As a result, the perturbations to the pulse are small enough that fundamental solitons are supported by the cavity, as demonstrated by three characteristic behaviors of the laser: The first is that the output pulses remain transform limited despite changes in average cavity GVD, pulse width, spectral bandwidth, and pulse energy. The second is that the soliton, or N, parameter is calculated by use of the operating parameters of the laser and remains within ±9% of unity for all operating modes, including multiple-pulse operation. The third is that, for some ranges of net cavity GVD, the laser exhibits a bistability and is capable of operation in either of two modes, each with a different number of transform-limited pulses in the cavity of different pulse widths. We compare this laser with other bulk solid-state lasers, demonstrating its differences and unique behavior not previously reported to our knowledge.

The Cr^{4+}:YAG laser has been mode locked by passive means such as Kerr-lens mode locking and with the use of a saturable Bragg reflector (SBR), producing pulses as short as 60 fs.[2–4] We have designed a short-cavity Cr^{4+}:YAG laser for high repetition rates, utilizing a SBR as the mode-locking device, as shown in Fig. 1.[5] One end of the 18-mm-long Cr^{4+}:YAG crystal rod (IRE-Polus) is polished flat and coated with a high reflector (HR), and the opposite end is polished to Brewster's angle. A 10-cm radius-of-curvature (RC) high-reflecting folding mirror provides astigmatic compensation, and a 7.5-cm radius-of-curvature 0.2% output coupler focuses the cavity mode to a spot size of 35 μm at the surface of the flat SBR. The structure of the SBR, shown in Fig. 1, consists of a 99.5% Bragg mirror of alternating quarter-wave layers of GaAs and AlAs and two uncoupled $In_{0.52}Ga_{0.48}As$/InP quantum wells located 15 nm from the top surface of a half-wave strain relief layer grown upon the final layer of the Bragg mirror. All reflectors are centered at 1550 nm, with the excitonic absorption of the quantum wells centered near 1500 nm. The output of a diode-pumped Spectra-Physics Nd:YVO_4 cw laser at 1062 nm is focused into the Cr^{4+}:YAG crystal through its flat end with 40- and 15-cm focal-length lenses. For compensation of the approximate 7 fs^2/mm of normal GVD ($\beta_2 > 0$) of the Cr^{4+}:YAG material at 1525 nm, bulk fused silica with -24.5 fs^2/mm of anomalous GVD is inserted into the cavity between the two curved mirrors by using two isosceles Brewster prisms (base widths of 18 mm) with as little tip-to-tip separation as possible (~1 cm). Because of this small separation, the geometrical GVD of the prism configuration can be ignored, and the result is essentially a Brewster plate with a variable optical thickness.

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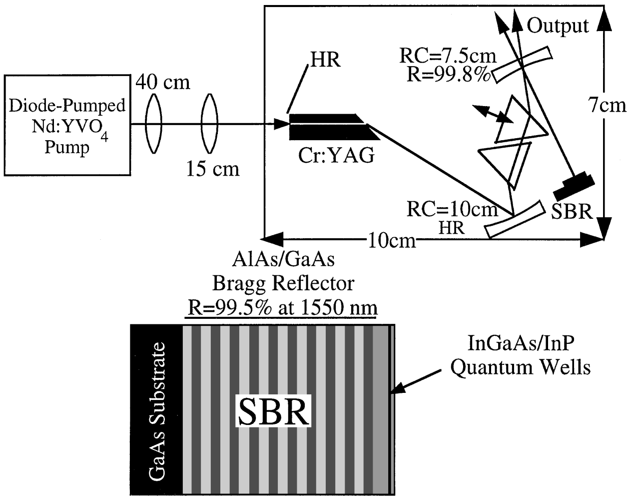

Fig. 1. Diagram of the laser cavity and structure of the SBR. R, reflectivity.

Simple cw cavity alignment produces stable self-starting mode locking of the laser as a result of the saturation dynamics of the SBR.[4,5] With approximately 7 W of incident pump power, 200-fs pulses (FWHM assuming a sech^2 pulse shape) are produced. Figure 2 gives a typical autocorrelation and optical spectrum of the output. For various regions of total cavity GVD the laser operates with one, two, or three pulses in the cavity. Figures 3 and 4 show the pulse width, the time–bandwidth product, and the total average power in the two output beams as a function of total cavity GVD illustrating these regions. The temporal intervals between pulses can either be equal (perfect harmonic operation) or differ by ≤10 ps from the ideal case; however, the intervals remain constant under stable operation. The intervals are measured with an optical cross-correlation technique that yields <100-fs accuracy. With three pulses in the cavity, a repetition rate of 2.7 GHz is reached with a total output power of 82 mW at a center wavelength of 1525 nm. Within some regions of cavity GVD the laser is bistable and can operate in modes with either two or three pulses in the cavity. The identical pulses of each mode have different widths and energies, as indicated by the dashed lines in Fig. 3. External perturbation of the laser is used to switch the number of pulses, to alter the intervals between pulses, or both. For all values of GVD and numbers of pulses in the cavity where stable mode locking is present the measured time–bandwidth product remains within 8% below 0.315, indicating that the pulses are transform limited, assuming a sech^2 profile, and some small asymmetry in the pulses may be present.

For fundamental soliton propagation the dispersion (L_D) and the nonlinear (L_{NL}) lengths (defined below) of the average GVD and SPM must be equal[1]:

$$L_D = \frac{{\tau_0}^2}{|\beta_2|}, \qquad L_{\mathrm{NL}} = \frac{1}{\gamma P_0}, \qquad \gamma = \frac{n_2 \omega_0}{c A_{\mathrm{eff}}}.$$

The variable τ_0 represents the pulse width, β_2 is the GVD, P_0 is the peak power, n_2 is the nonlinear refractive-index coefficient, ω_0 is the center optical frequency, A_{eff} is the effective area of the nonlinear interaction (the beam waist is taken to be 65 μm), and c is the speed of light. The soliton parameter (N), defined by $N^2 = L_D/L_{\mathrm{NL}}$, is unity for an ideal, chirp-free funda-

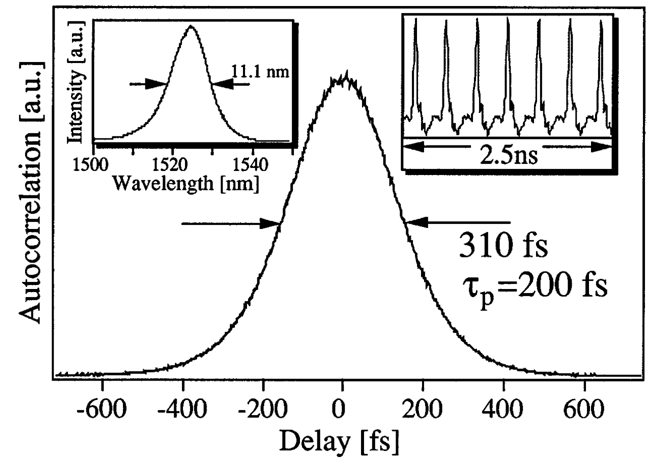

Fig. 2. Autocorrelation and optical spectrum (left inset) of the mode-locked output and a 2.7-GHz pulse train (right inset).

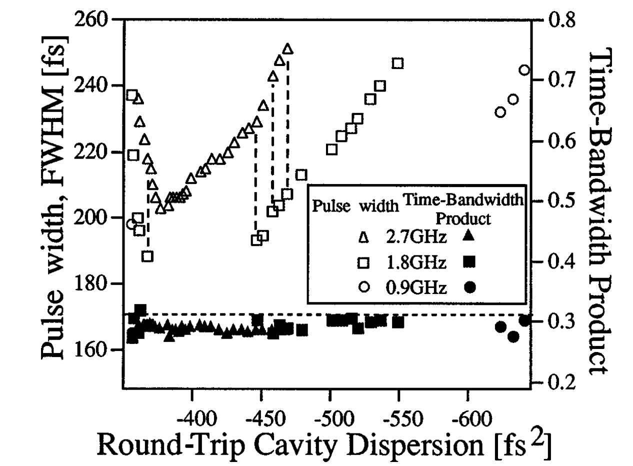

Fig. 3. Pulse width and time–bandwidth product of the mode-locked output with one (circles), two (squares), or three (triangles) pulses circulating in the cavity versus total cavity GVD.

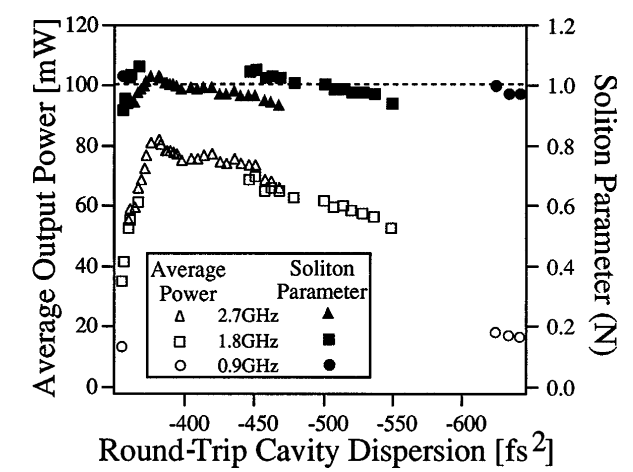

Fig. 4. Total average output power and soliton parameter of the mode-locked output with one (circles), two (squares), or three (triangles) pulses circulating in the cavity versus total cavity GVD.

mental soliton. For this laser, N is calculated at each point where stable mode locking is observed, by use of the average cavity and measured parameters, as shown in Fig. 4. The SPM and the GVD induced by the SBR are ignored in the present analysis. The value of N remains within $\pm 9\%$ of unity, suggesting that the pulses are fundamental solitons of the average GVD and SPM of the cavity. For a pulse to be described as a soliton in a laser cavity the perturbations caused by GVD and SPM in the cavity elements, either greater or less than the average, must be small, which we quantify by saying that both L_D and L_{NL} for the pulse in each of the perturbing media must be much longer than the physical lengths of that medium.[1] The Cr^{4+}:YAG material GVD is zero near 1581 nm and is only 7 fs^2/mm at 1525 nm, compared with 40 fs^2/mm in sapphire at 800 nm. Thus only a small amount of fused silica for GVD compensation is required, resulting in a 56-cm dispersion length for a 200-fs pulse, which is considerably longer than the ~ 1.5 cm of fused silica used in the cavity. The high repetition rates lead to small pulse energies, and the short cavity forces a large cavity mode in the gain crystal (50 μm at the high reflector, expanding to 110 μm at the Brewster end), which decreases the SPM experienced by the pulse compared with that in a standard 150-MHz cavity. For this laser, L_{NL} is of the order of 100 cm, which is considerably longer than that in the Cr^{4+}:YAG crystal. The SPM is ignored in the fused silica, as the beam radius is ~ 450 μm. Amplitude perturbations are small because gain, loss, and output coupling in this laser are low ($<1\%$ per pass). Thus the pulse experiences small perturbations as it propagates, and the effects of the GVD and SPM are balanced before the pulse width and the spectrum stray far from their average.

The production of transform-limited pulses in a bulk (nonfiber) solid-state laser over a wide range of cavity GVD has been demonstrated only in a Nd:glass laser with pulse widths greater than 800 fs.[6] The maintenance of time–bandwidth-limited pulses and the calculation of the soliton parameter in the presence of multiple pulsing have not been reported in a bulk solid-state laser to our knowledge. The commonly reported behavior in most solid-state lasers is that the pulse becomes chirped if the cavity GVD is varied away from that value that produces the shortest pulse. This is consistent behavior for a laser in which the pulse experiences large perturbations, and the pulse essentially undergoes compression and expansion in the various cavity elements during each round trip.[1] In some lasers the pulse width changes by as much as a factor of 5 in different regions of the cavity.[7] Additionally, L_D, L_{NL}, or both can be of the order of, or less than, the lengths of the individual cavity elements, preventing the formation of a fundamental soliton pulse. For these reasons, this laser is operating in a different regime from virtually all other solid-state lasers.

The multiple-pulse operation may be the result of the enhanced stability associated with pulses of lower energy and the reduction of the instabilities created by the periodic perturbations of the cavity elements. When the number of pulses circulating in the cavity increases, both L_D and L_{NL} increase and the relative strengths of the SPM and GVD perturbations decrease. Furthermore, a gain-bandwidth filtering effect that arises from the excitonic absorption of the SBR at shorter wavelengths and the decreasing gain of Cr^{4+}:YAG at longer wavelengths may also offer greater gain to a longer pulse with less optical bandwidth. An increase in the number of pulses in the cavity reduces the pulse energy and, with the influence of the soliton, lengthens the pulse, shrinking its optical bandwidth. An observed increase in the average output power accompanies the transition from two to three pulses in the cavity in a region of bistability, indicating a greater gain for the longer pulses. Without the fused-silica prisms in the cavity, chirped 1.5-ps pulses are obtained. This suggests the passive pulse shortening strength of the SBR, which is believed to be the cause of the apparent upper limit of the pulse width (Fig. 3) and the reason for the transitions to fewer and shorter pulses in the cavity as the GVD is increased.

In conclusion, we have demonstrated a short-cavity passively mode-locked Cr^{4+}:YAG laser that possesses relatively small perturbations to the pulse from GVD and SPM such that stable fundamental solitons circulate in the cavity. The pulses remain transform limited and the calculated soliton parameter remains near unity despite large changes in the average cavity GVD and pulse energy. Regions of bistability exist where, at a single value of cavity GVD, the laser supports transform-limited pulses with different widths and pulse energies, further indicating that the intracavity pulse is a fundamental soliton. An aggregate repetition rate of 2.7 GHz is reached with a total of 82 mW of average output power consisting of 200-fs pulses.

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