Observation of High-Order Solitons Directly Produced by a Femtosecond Ring Laser

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We report here the first experimental observation of $N=3$ solitonlike pulses generated by a passively mode-locked ring laser at 620 nm. The evolution of the pulse shape is recorded along the soliton period corresponding to about 2400 cavity round trips. Experimental indications of the soliton character of any pulse produced by this type of laser are also obtained. Properties of high-order solitons could offer new possibilities of intracavity pulse compression.

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For a few years the production of ultrashort pulses in colliding-pulse mode-locked (CPM) dye lasers has been widely studied,[1–4] and pulses shorter than 0.1 ps are now currently obtained in the 620-nm region. However, many questions remain to be solved about the physical mechanism of the generation of these pulses. Recent theories[4,5] introduce both self-phase-modulation and group-velocity dispersion in the equations which describe the pulse evolution during a single cavity round trip. The mathematical form of these equations has led to consideration of a "soliton-type shaping mechanism" yielding a squared-hyperbolic-secant (sech^2) pulse shape.

On the other hand, the propagation of solitons in nonlinear media without loss or gain, described by a wave equation which has the mathematical form of a nonlinear Schrödinger equation,[6] has been considered with great interest. Such soliton effects have been observed for pulse propagation in monomode optical fibers at wavelengths longer than 1.3 μm,[7] and for the inhomogeneous plane-wave self-guiding of light in nonlinear media.[8] But, to our knowledge, the soliton character of the pulses produced by CPM lasers has not yet been clearly evidenced.

In this Letter we report the first (as far as we know) experimental observation of soliton bound states (N-order solitons) directly produced by a CPM laser at a wavelength of about 620 nm. This soliton effect appears as a periodical variation in the temporal shape of the pulses generated by the laser. Here, we particularly analyze the $N=3$ soliton behavior and we present the evolution of its autocorrelation function during the soliton period which corresponds to about 2400 cavity round trips. We also check the agreement of some of our data with basic soliton formulas and suggest a future theoretical approach. We think that high-order solitons could be used experimentally to produce ultrashort light pulses by intracavity compression.

The results presented in this Letter have been obtained from a homemade CPM laser[9] using rhodamine 6G and diethyloxadicarbocyanine iodide (DODCI) dyes, pumped by a cw argon-ion laser. The ring laser cavity contains a sequence of four prisms that allow a precise adjustment of the group-velocity dispersion (GVD) from a positive to a negative value.[10] When the GVD is increased by translation of one prism (which introduces a larger glass thickness in the beam path), the pulse width, measured with an optical autocorrelator,[11] decreases to about 70 fs, assuming a sech^2 pulse shape (such a behavior is in agreement with the theoretical analysis of Martinez, Fork, and Gordon[5]). If we go on introducing more glass, this theoretical model predicts "an unstable region" where the sech^2 pulse shape cannot exist any more. We have actually observed instabilities characterized by a noisy autocorrelation trace and pulse-train envelope, and accompanied by a decrease of the output power from 10 to 3 mW and an increase of the central wavelength from 612 to 618 nm.

However, this apparently unstable regime may be stabilized by a decrease of the pump power down to about 0.1 W above the laser threshold power (2.3 W all lines). The autocorrelation function becomes less noisy and presents a triple-humped shape [Fig. 1(a)], while a regular modulation at about 70 kHz appears on the pulse-train envelope [Fig. 1(b)]. Such behavior, not predicted by existing theories, has already been reported by other authors[2,12] without any interpretation.

We think that it is possible to interpret these phenomena as an $N=3$ solitonlike behavior, with a periodical evolution characterized by the two frequencies 35 and 70 kHz found by a more careful spectrum

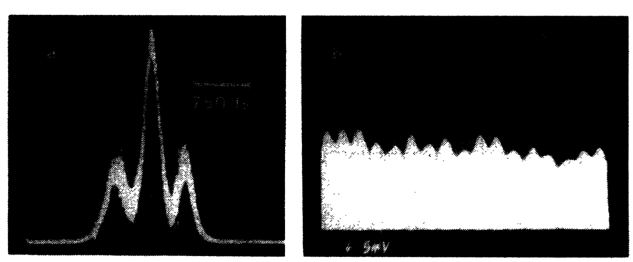

FIG. 1. (a) Autocorrelation trace obtained with an excess of positive GVD; (b) pulse-train envelope under the same experimental conditions.

analysis of the electrical signal shown in Fig. 1(b). For the sake of clarity, we recall some basic properties of solitons, first deduced by Zakharov and Shabat[6] for nonlinear media without loss or gain. According to these results, the evolution of the envelope of an N soliton is characterized by $N-1$ frequencies. For instance, Fig. 2 shows a perspective plot of the temporal pulse shape at various Z along the nonlinear medium for the $N=3$ soliton, on the assumption of an initial sech^2 pulse shape.

The parameter Z_0 corresponds to the length of nonlinear medium at which the pulse shape is restored. Z_0, which is actually independent of the soliton order, is given by[13]

$$Z_0 = 0.322\pi^2\tau^2 c/\lambda^2 D, \tag{1}$$

where D is the GVD of the medium (in fs/km·nm), λ is the vacuum wavelength, c is the vacuum velocity of light, and τ is the usual experimental pulse width (full width at half maximum of intensity). In our case, the relevant quantity is the GVD per cavity round trip Dl, where l is the length of nonlinear medium in the cavity. We relate this quantity to the usual cavity dispersion ϕ'' (in femtoseconds squared) by

$$\phi'' = (\lambda^2/2\pi c)Dl. \tag{2}$$

Using this relation, one finds that the pulse shape is restored after N_0 round trips in the cavity, with

$$N_0 = Z_0/l = 0.322\pi\tau^2/2\phi''. \tag{3}$$

Since our cavity round-trip time is $T=12$ ns the correspondent soliton frequency is

$$f_0 = \frac{1}{N_0 T} = \frac{2\phi''}{0.322\pi\tau^2 T}. \tag{4}$$

For fixed ϕ'' and τ parameters, f_0 is always the lowest of the $N-1$ characteristic frequencies of an N soliton.

In our case we have observed two frequencies in the modulation of the pulse-train envelope. According to our interpretation the lowest ($f_0 = 35$ kHz) is the fundamental soliton frequency corresponding to $N_0 \cong 2380$ cavity round trips [Eq. (4)]. The appearance of a second frequency at twice the fundamental one is due to the particular evolution of the $N=3$ soliton, which becomes very sharp two times during each soliton period[14] ($Z=Z_0/4$ and $Z=3Z_0/4$ in Fig. 2).

Direct evidence of the above assertions is obtained by our recording the evolution of the pulse autocorrelation function during the soliton period. This was achieved by analysis of the output signal of the autocorrelator using a sampler averager triggered synchronously with the 35-kHz modulation. The window of the sampler is about 100 ns and its opening edge may be shifted relative to the 35-kHz modulation phase. This experimental procedure is equivalent to the recording of the autocorrelation function of pulses selected at a given time in the soliton period. Figure 3 shows three autocorrelation functions obtained by increasing of the phase shift from 0° to 180° in 90° steps (the phase shift yielding the maximum width for the autocorrelation trace is arbitrarily taken equal to 0). These results are clearly consistent with the theoretical $N=3$ soliton evolution sketched in Fig. 2. Together with this autocorrelation evolution, we have observed an evolution of the spectrum of the pulses. The most striking feature here is that a hole is periodically dug at the center of the spectrum at a frequency of 35 kHz. This hole is at its maximum depth when the autocorrelation is triple humped, which is consistent with calculated $N=3$ soliton spectra evolution.[13] We note that we used this 35-kHz modulation to drive the sampler averager.

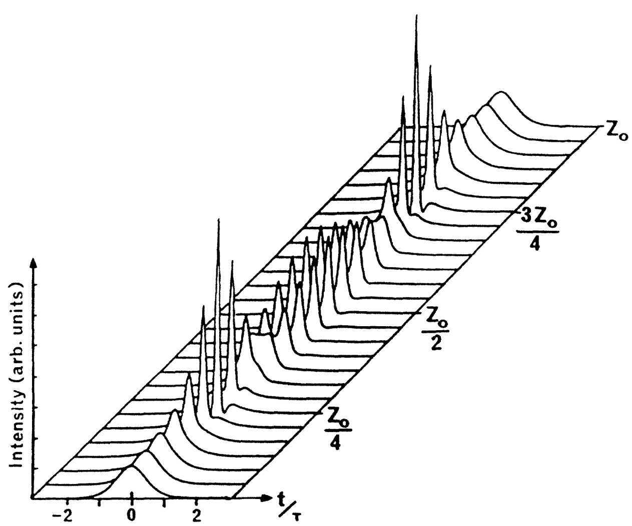

FIG. 2. Perspective plot of an $N=3$ soliton temporal shape at different points of the soliton period. τ is the full width at half maximum of the initial pulse intensity and Z_0 is the length of medium at which the pulse is restored.

In order to check more precisely Eq. (4), we have measured the variation of the soliton frequency Δf_0 as a function of the cavity-dispersion variation $\Delta\phi''$. ϕ'' is changed by the translation of one prism in the ring cavity. For a variation ΔL of the glass pathway inside the cavity, $\Delta\phi''$ is given by

$$\Delta\phi'' = -\frac{\lambda^3}{2\pi c^2}\frac{d^2n}{d\lambda^2}\Delta L, \tag{5}$$

where n is the prism refractive index. The results are plotted in Fig. 4 and exhibit a nearly linear relationship between Δf_0 and $\Delta\phi''$ which indicates that τ is roughly constant over our dispersion-variation range. The slope is 0.725 ± 0.05 kHz/fs^2 which yields a τ value of 475 fs [Eq. (4)]. An estimation of pulse widths from

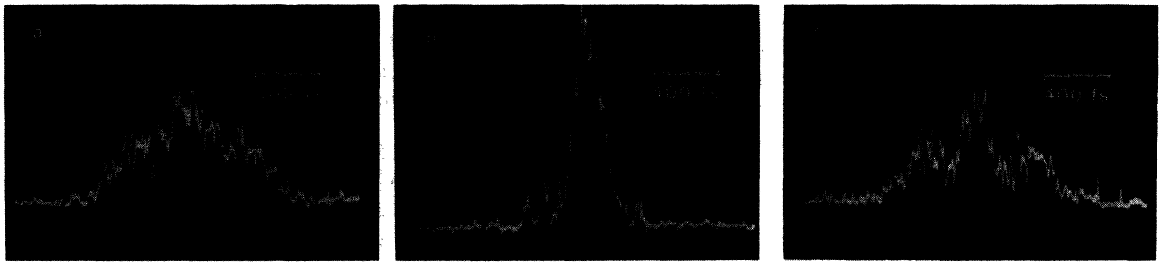

FIG. 3. Autocorrelation functions measured with a sampler averager. The phase shift between the driving modulation and the analyzing window train is (a) 0°, (b) 90°, and (c) 180°. Note that a phase shift of 90° corresponds to a cavity-round-trip shift of 600.

autocorrelation traces remains consistent with the above value of τ. The corresponding value of ϕ'' given by Eq. (4) is $|\phi''| = 55\ \text{fs}^2$ for $f_0 = 40$ kHz.[15] We note here that, by translating the DODCI jet without moving the prisms, we have also obtained autocorrelation functions indicating the existence of $N=1$ up to $N=3$ solitons which all have the same center wavelength and nearly the same characteristic duration ($\cong 470$ fs). As we said at the beginning of this Letter, our CPM laser can also produce pulses with a 70-fs minimal width and a 50-Å-shifted central wavelength. This regime seems to correspond to another $N=1$ soliton, but higher-order solitons belonging to this regime have not yet been observed. The 70-fs $N=1$ soliton cannot be obtained from the $N=3$ soliton described in this Letter by a mere translation of the DODCI jet (variation of the power density in the saturable absorber), but also needs a translation of the prisms.

In summary, we have observed for the first time an $N=3$ soliton in the visible domain directly produced by a CPM laser. We have performed a time analysis of the evolution along the $N=3$ soliton period corresponding to about 2400 cavity round trips and given indications for the existence of other order solitons.

Such behaviors are not predicted by existing theories of CPM lasers but are very close to the predictions of the nonlinear Schrödinger equation describing pulse propagation in a homogeneous medium with group-velocity dispersion and self-phase-modulation. Obviously our laser differs from such a medium in several respects. First, the laser cavity is a composite system where self-phase-modulation and group-velocity dispersion can be separately controlled by external parameters (e.g., prism positions, dye-jet properties, mirror coatings). Moreover, since the soliton period is about 2400 cavity round trips, it appears that the total group-velocity dispersion and self-phase-modulation per round trip are very small fractions of those corresponding to the restoration of the pulse shape. Second, the laser includes both saturable gain and loss which are not taken into account in the usual soliton equations. As a result of these mechanisms, the pulse energy may change along the soliton period. This fact was invoked above to explain the modulation of the pulse-train envelope.[16]

In order to interpret our experimental results one could suggest a theoretical approach based on the nonlinear Schrödinger equation but including dispersive and saturable loss and gain and collision of pulses. Such an approach has been initiated, for instance, by Haus and Islam[17] to describe an infrared laser including an intracavity optical-fiber shaping mechanism.[18]

Another theoretical possibility would be a numerical method in which the pulse shape offers only a slight change during a single cavity round trip, but is restored after a very large number of them. Our laser offers a unique possibility to test theoretical predictions at every step of the pulse evolution.

Further progress in the production of higher-order solitons (i.e., starting from the shortest $N=1$ soliton) could offer new possibilities of intracavity pulse compression by extraction of the pulse at a narrower point of its periodical evolution.

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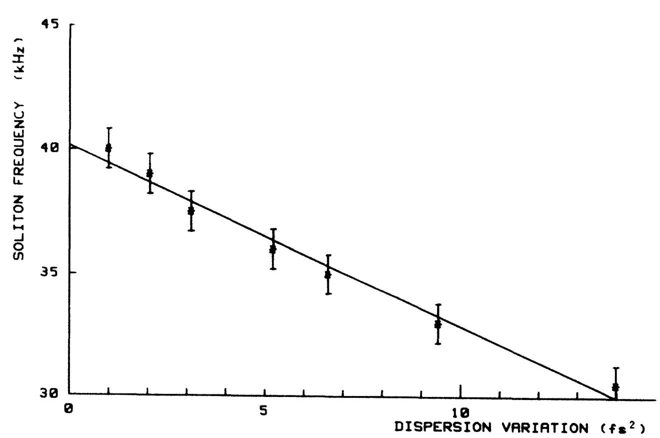

FIG. 4. $N=3$ soliton frequency vs cavity dispersion ϕ''.

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[14]We believe that such a shape may introduce variations on the gain parameter of the laser and therefore on the pulse energy which then explains the modulation of the pulse-train envelope. See also the last part of this Letter.

[15]A similar linear relationship has been found between Δf_0 and the variation of the average output power of the laser, which seems in accordance with usual soliton formulas (Ref. 13).

[16]Moreover, even in the case of the 70-fs $N=1$ soliton (usual regime of the CPM laser) we have observed a small modulation of the pulse-train envelope. For instance, for a pulse width of 70 fs the modulation frequency is about 1.5 MHz. Using Eq. (4) with the experimental values $\tau=70$ fs and $\phi''=55$ fs^2, we obtained a soliton frequency of about 1.85 MHz, in very close accordance with the measured value. The nonlinear Schrödinger equation predicts only a periodical phase shift of the $N=1$ soliton at the soliton frequency given by Eq. (4). This shift could explain the observed energy modulation if one would take into account saturable and dispersive gain.

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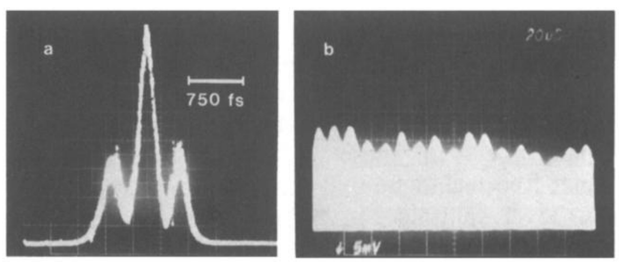

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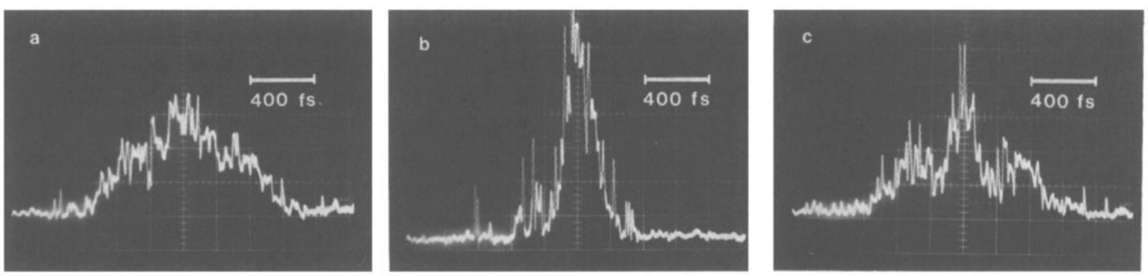

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