

NON SYMMETRICAL N = 2 SOLITONS IN A FEMTOSECOND DYE LASER

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François Salin, Philippe Grangier, Gérard Roger, Alain Brun. NON SYMMETRICAL N = 2 SOLITONS IN A FEMTOSECOND DYE LASER. Journal de Physique Colloques, 1988, 49 (C2), pp.C2-491-C2-494. 10.1051/jphyscol:19882115. jpa-00227626

HAL Id: jpa-00227626 https://hal.science/jpa-00227626

Submitted on 4 Feb 2008

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<u>Résumé</u> - Nous présentons la première observation expérimentale de solitons d'ordre 2 non-symétriques. Ces impulsions sont produites par un laser à colorant à blocage de mode passif. L'évolution du spectre des impulsions à été enregistrée et elle est comparée aux prédictions théoriques de l'équation non-linéaire de Schrödinger.

<u>Abstract</u> - We report here the first experimental observation of non symmetrical N = 2 soliton like pulses. These solitons are produced by a passively mode-locked dye laser. The pulse spectrum evolution has been recorded and compared with theoretical predictions of the nonlinear Schrödinger equation.

Since the first production of subpicosecond pulses by using passive modelocking of dye lasers [1], great progresses have been achieved. Introducing systems to control the intracavity group velocity dispersion (GVD), pulse durations as short as 30 fs have been obtained [2]. It is now well established that soliton mechanisms (i.e. balancing between self phase modulation and group velocity dispersion) are responsible for formation and shortening of pulses in these passively modelocked and dispersion controlled lasers [3, 4]. Femtosecond pulses have also been produced using either fiber Raman amplified soliton lasers working in the 1.5 μ m range [5], or soliton narrowing in optical fibers [6, 7]. In all works dealing with temporal solitons propagation [4, 7], spatial solitons self-guided propagation [8], or theoretical studies on soliton lasers [9], only symmetrical shapes were considered. This leads to the misconception that solitons could only have symmetrical shapes. In this paper, we report the first (as far as we know) observation of the time evolution of non symmetrical N=2 solitons. These pulses are directly produced by a colliding pulse modelocked (CPM) laser. This experimental observation shows that CPM lasers can be considered as class of soliton lasers.

With use of the slowly-varying-envelope approximation, pulse propagation in a non-linear medium can be described with the so-called non-linear Schrödinger equation (NLSE). The pulse envelope amplitude u(z,t) satisfies the following equation :

 $i \frac{\partial u}{\partial z} + \frac{1}{2} \frac{\partial^2 u}{\partial z^2} + |u|^2 u = 0$ (1)

where t is the pulse local time and z is the normalized distance in the propagation medium.

Zakharov and Shabat [10] have shown that the NLSE can be solved by the inverse scattering method. The stable solutions for propagation are called soliton bound states. Each solution is characterized by a set of complex constants $\{\xi_j, C_j\}_{j=1,...,N}$. The complex ξ_j 's are the poles of the soliton and the C_j 's its residues. For an N = 2 soliton Zakharov and Shabat [10] and Haus and Islam [9] have shown that the 4 degrees of freedom of the complex residues C_j 's and poles ξ_j 's affect the soliton in restricted ways and that an N=2 soliton is uniquely described by a set of four real constants $\{\eta_1, \eta_2, C_1, C_2\}$. Symmetrical solitons are obtained when residues are related by [9]:

$$C_{j} = \prod_{k=1}^{N} (\eta_{j} + \eta_{k}) / \prod_{\substack{k=1 \ k \neq j}}^{N} |\eta_{k} - \eta_{j}|$$
(2)

Note that even for the restricted case of symmetrical solitons, one can find an infinity of N=2-solitons. The usual solution characterized by u (z = 0,t) = 2 sech (t) corresponds to poles $\eta_1 = 1/2$ and $\eta_2 = 3/2$, and to residues $C_1 = 2$ and $C_2 = 6$. When Eq. (2) is not verified, the N=2 soliton temporal shapes generally present a double hamped structure with one of the peaks much higher than the second one [11]. All these N=2-solitons present a periodical evolution of their shape. The period T_p only depends on the pole values [9]: $T_p = \Pi/(\eta_2^2 - \eta_1^2)$. As an example, evolutions of an N=2 soliton temporal shape and spectrum during a period T_p , are sketched on Fig. 1, for $\eta_1 = .7$, $\eta_2 = 1.3$, $C_1 = .7$ and $C_2 = 1.1$ (the sum of the poles is chosen to give $\eta_1 + \eta_2 = 2$, in order to have the same energy as the solution given by u (z, t)).



Figure 1 : Theoretical evolution of a non symmetrical N=2 soliton : a) temporal pulse shape ; b) pulse spectrum.

Such a non symmetrical soliton is not easily experimentally observed because it is very difficult to generate the exact shape u(z=0,t) in amplitude and phase before launching the pulse in a non-linear medium. In the experiment described here, the generating and propagation media are not separated. We have used a CPM dye laser containing a sequence of four prisms which allows a precise adjustment of the GVD inside the cavity [2]. In its usual working regime, our laser produces stable pulses with duration as short as 40 fs at 620 nm. These pulses correspond to N=1 solitons [4]. If we introduce in the cavity less negative dispersion than the value corresponding to the minimum pulse width, the laser wavelength shifts toward the red. By focusing or defocusing the laser beam spot in the DODCI jet, and thus varying the ident optical power density, we are able to obtain N=1, N=2 and N=3 solitons at 622 nm. These pulses are characterized by a modulated pulse train envelope with the (N-1) characteristic frequencies of a N soliton. In a recent paper [4] we have studied the evolution of the pulse temporal shape in N=3 soliton regime.

In order to study N=2-solitons, the beam spot in the DODCI jet was defocused until only one frequency (near 80 kHz) was observed in the pulse-train envelope modulation. The pulse autocorrelation functiovariation of the amplitude of the wings and a small increase of the autocorrelation maximum between the beginning and the middle of the period. The fact that the pulse wings never disappear during the period seems to indicate that this N=2 soliton does not correspond to the classical N=2 soliton with $U(Z=0,t) = 2 \operatorname{sech}(t)$.

In order to obtain more informations on the exact profile of this pulse, we have recorded the evolution of its spectrum along the soliton period. We

have used an optical multichanel analyzer triggered synchronously with the pulse train envelope modulation. Fig. 2 shows the experimental recordings of the pulse spectrum evolution along one soliton period T_p . This figure is clearly consistent with the spectrum evolution of a non symmetrical N=2-soliton.



Figure 2 : Experimental recording of the pulse spectrum evolution during a soliton period. Note that the shift between each curve corresponds to about 70 cavity round trips. It can be deduced from the comparison between these results and Fig. 1 that the large intensity peak occurs before the small one.

We have tried different combinations of poles and residues values in Eq. 3, in order, to obtain a general evolution of the soliton autocorrelation and spectrum close to the experimental results. As exhibited on Fig. 1.b, the set of values $\eta_1 = .7$, $\eta_2 = 1.3$, $C_1 = .7$, $C_2 = 1.1$ gives a reasonable fit with experimental data.

It can therefore be concluded that the CPM laser produces pulses with changing temporal shapes, which can be described by theoretical results for a N = 2 soliton, at least as a first approximation. This result suggests to use a perturbation technique on the NLSE [5], in order to determine why and how the laser selects a particular type of soliton. Satsuma and ima [13] and Haus and Islam [9] have shown that a small variation in the pulse profile (due to saturable gain or losses) can be taken account by introducing a motion of the soliton poles and residues. We think that, as gain and losses depends on the exact pulse profile which varies periodically, the soliton poles motion should be periodic. This periodic evolution of the pole could explain the observed energy modulation of the pulses produced by the laser. Moreover, some mechanisms non symmetrical relative to the pulse local time, such as self-phase modulation [12] or higher dispersion effects, could explain the production of non-symmetrical solitons.

In conclusion we present here the first experimental observation of a non symmetrical soliton. We have performed a spectrum analysis of its evolution along the soliton period. This result indicates that, in this particular regime, a CPM laser produces double peaked pulses whith a shape evoluating with a 1100 cavity round trips period. The remarkable consistency of these experimental results with the non linear Schrödinger equation, (even if the non linear properties of the laser cavity are much more complex than those supposed in this equation) suggests a new approach for the theoretical description of CPM lasers.

This work is supported in part by the Ministère de la Recherche Scientifique and by the Direction des Recherches et Etudes Techniques (Division Optique).

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