Improved mode locking of an F-center laser with a nonlinear nonsoliton external cavity

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We demonstrate that solitons are not essential for the operation of the soliton laser. The external cavity employed contains an optical fiber with negative group-delay dispersion and therefore does not support bright solitons. Thus the improved mode locking cannot be attributed to the injection of an $N = 2$ soliton.

The soliton laser[1] was the first example of a nonlinear external cavity's being used to improve the mode-locked performance of a laser. The configuration used is shown in Fig. 1. The external cavity contains a monomode optical fiber with positive group-delay dispersion, thus supporting soliton solutions.[2] When the length of the external cavity is such that the returned pulse is synchronous with the pulse in the fundamental laser cavity, then the mode-locking bandwidth can be greatly enhanced, and pulses with a duration much shorter than those produced by the laser alone are observed. The explanation of this effect uses the properties of the soliton solutions of the nonlinear Schrödinger equation, which describes the propagation of light in optical fibers. In particular the $N = 2$ soliton evolves periodically with fiber length. Thus if the external fiber has a length equal to the soliton period, then the pulse returning to the fundamental cavity will be identical in shape to the previous laser pulse, completing the feedback loop. This simple operating point describes the main principle of the device but is somewhat over simplified. The first double-cavity theory of the soliton laser[3] and further experimental studies[4] have emphasized the importance of the interferometric mismatch between the two cavities and also indicated the existence of many operating points that were not always related to the $N = 2$ soliton.[1]

A more recent theory[5] has considered the coupling of an actively mode-locked laser to an external cavity containing a nonlinear element described through a simple transfer function. Two nonlinearities were considered that had different effects on the pulse shaping. The first was a saturable absorber, which gives pulse compression similar to the propagation effects observed during soliton propagation. The second was a saturable amplifier, which leads to pulse broadening similar to the nonlinear propagation in a fiber with negative group-delay dispersion.[6] The surprising result was that both nonlinear responses lead to the prediction of shorter pulses from the coupled-cavity system. The main difference in operation between the two nonlinearities was in the value of the optimum cavity phase mismatch. The proposed explanation for this effect[5] is that the nonlinear response of the external cavity causes coupling between the longitudinal modes of the laser. This coupling allows better communication of phase information between the modes, with a consequent increase in the mode-locked bandwidth. Thus the behavior of the soliton laser may be more correctly described in terms of injection locking, and a theoretical approach along these lines has already achieved some success.[7] The implication of these theoretical conclusions is that the soliton laser is one example of a much wider class of systems in which the external cavity has some nonlinear response but does not necessarily support solitons or solitary waves.

To examine these possibilities we have performed some experiments based on the soliton-laser configuration, but with some differences. A Burleigh Tl:KCl color-center laser, synchronously pumped by a cw mode-locked Quantronix 416 Nd:YAG laser, was coupled to an optical fiber in an external cavity with the correct length to ensure synchronism between the two cavities. The color-center laser was operated at 1.5 μm, and in the absence of any optical feedback it produced pulses with an autocorrelation FWHM of 20 psec. We began by using a positive group-delay dispersion fiber as the nonlinear feedback element and established the existence of many operating points as indicated by previous experiment[4] and theory.[3] The fiber was a standard communication-grade fiber with a dispersion of 16 psec/nm · km and a core area of 50

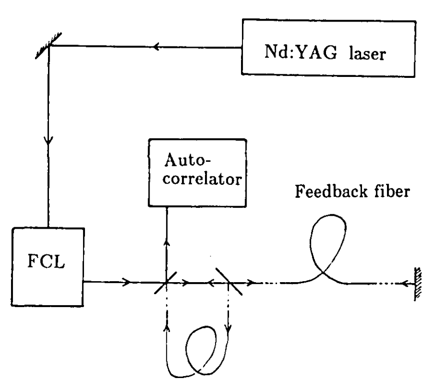

Fig. 1. The experimental configuration. FCL, F-center laser.

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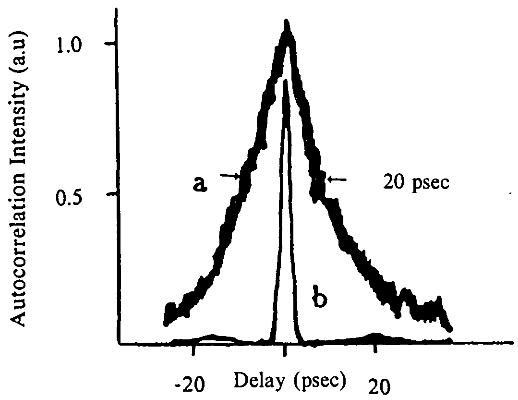

Fig. 2. Normalized autocorrelation traces of the laser system operating without optical feedback (curve a) and with optical feedback (curve b). The baseline is also indicated.

μm^2. We obtained operation of the soliton laser over a wide range of average launched power (4–40 mW) for a fixed fiber length of 20 m. The calculated range of N is 1.56–4.95, which demonstrates that the $N = 2$ soliton picture is incomplete.

To investigate other operating points a different nonlinear feedback element was used. We still used an optical fiber but intentionally selected a fiber where (bright) solitons are not supported, namely, where the group-delay dispersion is negative. In this dispersion regime the combined effects of the nonlinear response of the fiber and its dispersion lead to enhanced pulse broadening.[6,8,9] Thus, although the nonlinear response of this fiber is more complicated than those used in the theoretical calculations, it is analogous to the response of the saturable amplifier in that the nonlinear response of the fiber causes pulse broadening. The configuration (Fig. 1) was the same as that of the soliton laser, but we used an optical fiber with a dispersion zero shifted to a long wavelength, >1.6 μm, as we prove below. The fiber has a dispersion of -10 psec/nm · km and a core area of 28 μm^2.

We observed a decrease in the system pulse width in much the same way as that observed in the soliton laser. In Fig. 2 we show (normalized) background-free autocorrelation traces of the laser alone (curve a) and the laser coupled to the external cavity (curve b). The reduction in pulse autocorrelation width can clearly be seen, from 20 to 3.0 psec, and is quite similar to results obtained with the soliton laser.[1] This present result was obtained with a 2.4-m length of optical fiber at an average launched power of 9 mW. We performed a number of measurements of pulse width as a function of average launched power and fiber length. These results are shown in Fig. 3(a). The spread of results shows the existence of a large number of operating conditions. To analyze these results we now generalize the $N = 2$ soliton explanation[1] to include our nonsoliton fiber. The essence of that explanation was that the laser mode locking is dominated by the $N = 2$ soliton. The generalization of this explanation is that the laser mode locking is dominated by the nonlinear properties of the optical fiber. We assume that the same normalized solution of the nonlinear Schrödinger equation represents the stable state of the laser system for all fiber lengths. We can now use the scaling properties of the nonlinear Schrödinger equation, which are identical to those used for the $N = 2$ soliton and hold generally for any normalized solution,[3] to relate the normalized fiber length to the physical system parameters. This normalized length is given by

$$L_{\text{norm}} = \left(\frac{k_2}{\tau^2}\right) z, \tag{1}$$

where k_2 is the fiber dispersion, τ is the pulse width, and z is the fiber length. We note that the $N = 2$ soliton explanation proceeds in the same way by fixing L_{norm} at $\pi/2$ to obtain the scaling relation $\tau \sim z^{1/2}$, but we also note that obeying this relation is not evidence for the $N = 2$ soliton per se; rather, it is evidence for the dominant role of the nonlinear Schrödinger equation. In Fig. 3(b) we have shown the relationship between L_{norm} calculated from Eq. (1) and P obtained from our measurements. The measurements on the

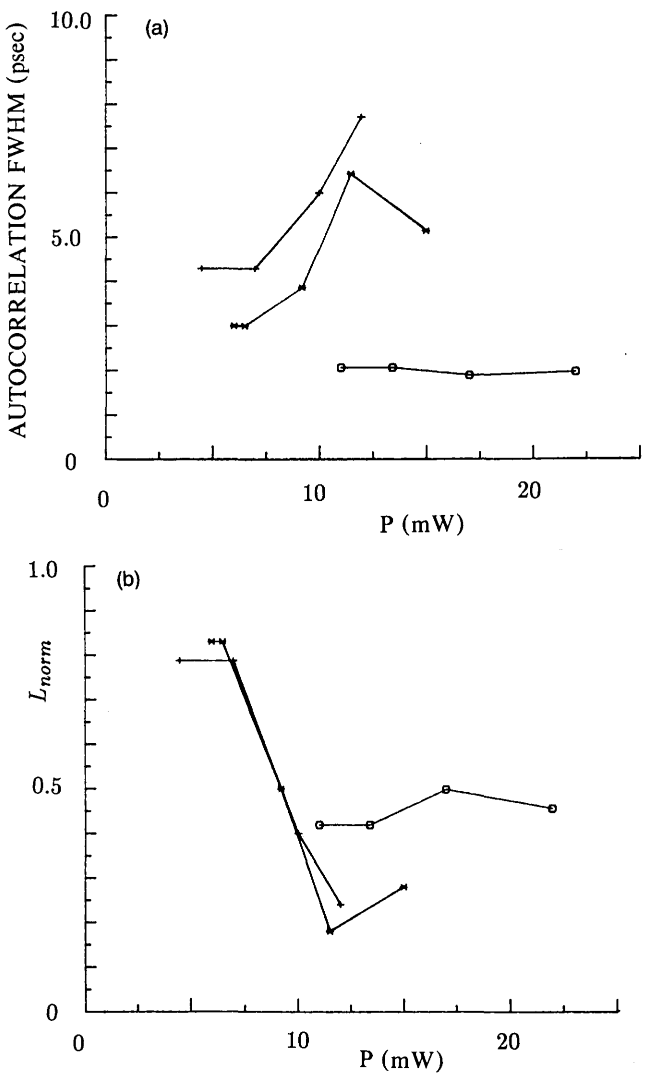

Fig. 3. (a) Autocorrelation FWHM obtained at different operating points for various lengths of fiber (+, 20 m; *, 10 m; o, 2.4 m). (b) The results in (a) scaled using Eq. (1) to obtain the normalized fiber length.

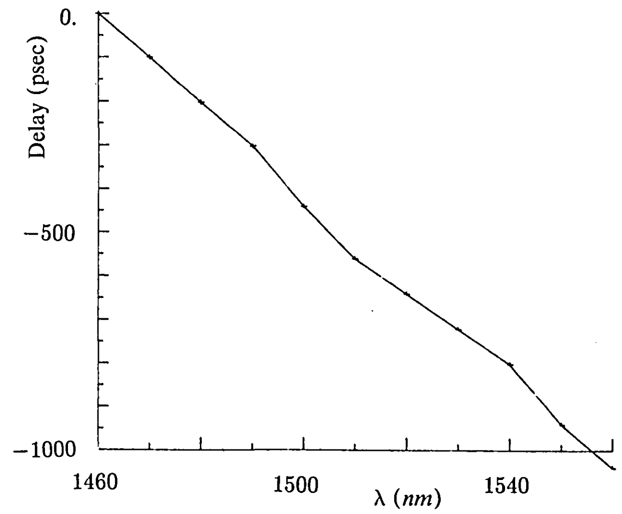

Fig. 4. Group-delay curve for 1 km of the nonsoliton fiber used in this experiment.

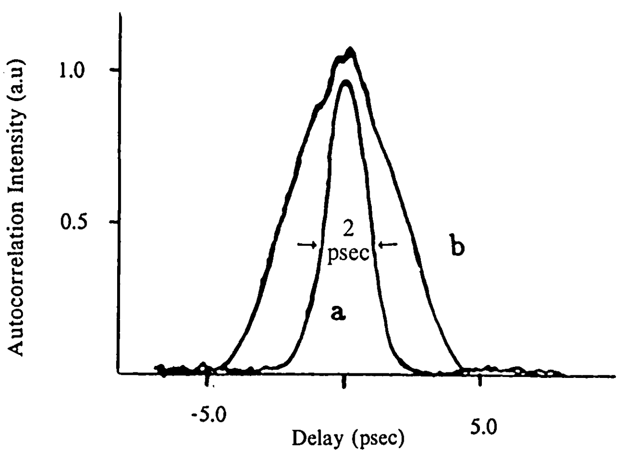

Fig. 5. Curve a, input soliton-laser pulse to the 20-m length of nonsoliton fiber used in this experiment. Curve b, output autocorrelation trace obtained at an average launched power of 5 mW. The baseline is also indicated.

two longest lengths of fiber (10 and 20 m) are well correlated, and the results from the shortest fiber (2.4 m) give normalized fiber lengths in the same range. The system pulse width tends to increase with launched power, although this is not evident in the shortest fiber. The good correlation between the two longer fibers confirms the dominant role of the nonlinear Schrödinger equation in determining the properties of this system. The dependence of the normalized fiber length on input power also shows that many solutions of the nonlinear Schrödinger equation can act as operating points. The optimum normalized fiber length for this system is somewhat shorter than that of 0.4 (Ref. 4) obtained in the soliton laser.

Since the results presented here are contrary to the conventional understanding, we need to establish beyond any doubt that the length of fiber we used had negative group-delay dispersion. A simple group-delay measurement on a 1-km length of the fiber was made by tuning the color-center laser over its full range (without any external cavity). The group-delay curve is shown in Fig. 4, and from this the fiber dispersion was measured to be −10 psec/nm/km. However, in order to be sure that the actual length of fiber used in this experiment had negative dispersion and was not positive owing to some longitudinal inhomogeneity in the fiber, we performed a second measurement. We set up the standard soliton-laser configuration that produced pulses with an autocorrelation FWHM of 2 psec. These pulses were then launched into the same 20-m length of fiber used in our nonlinear external-cavity experiment. Figure 5 shows the input (curve a) and output (curve b) autocorrelation traces at a launched power of 5 mW. The output pulse is broader by a factor of approximately 3, and the shape is somewhat triangular, which is consistent with the pulse-shaping effects normally observed in the negative group-delay dispersion regime.[6] Since the power level used in this measurement is comparable with those used in the external cavity, we can also see that the pulse returned to the laser cavity by the 20-m length of fiber will be broader than the output pulse. These measurements establish that, whatever the role of the fiber turns out to be, it is not necessary that it supports solitons.

In conclusion, we have observed enhanced mode locking similar to that of the soliton laser using an optical fiber that does not support solitons at 1.5 μm. The fiber used in the external cavity had negative group-delay dispersion, and hence the nonlinear response is to broaden pulses temporally. However, the pulses are also broadened spectrally, which leads to the improved transmission of phase information through the gain bandwidth of the laser. The results that we have obtained obey approximately the scaling relations of the nonlinear Schrödinger equation, as has been predicted.[3] We have also presented linear and nonlinear measurements on the 20-m length of fiber used in the external cavity that clearly show that the fiber does not support solitons at the operating wavelength.

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