Enhanced mode locking of color-center lasers

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A significant enhancement in the mode locking of a KCl:Tl color-center laser has been observed when a length of optical fiber having positive group-velocity dispersion was incorporated within an external control cavity. Pulse durations of ~260 fsec were obtained by this method, representing a compression factor ~60× that with the color-center laser alone. Similar results have also been observed with an InGaAsP semiconductor diode amplifier as the nonlinear element within the control cavity.

The synchronously mode-locked KCl:Tl color-center laser can typically produce pulses of ~8–20-psec duration at a wavelength of approximately 1.5 μm. In the research by Mollenauer and Stolen,[1] the mode-locked characteristics of such a laser were dramatically improved by incorporating a length of optical fiber into an optical feedback loop, or control cavity. A small fraction of the output from the color-center laser was fed into the fiber, where the combined effects of self-phase modulation and negative group-velocity dispersion (GVD) caused the pulses to be temporally compressed. These compressed pulses are then reinjected into the master cavity, stimulating the production of narrower pulses from the laser itself. This process continues until the pulses have essentially the same shape on entering and returning from the fiber, i.e., they become optical solitons. Although it was observed that for a single length of fiber a variety of pulse durations could be obtained,[2] the pulses returning from the control cavity and injected back into the laser were always observed to be as short or shorter than those exiting the composite cavity laser. In this Letter we describe experiments whereby an optical fiber having positive GVD was inserted into a control cavity (similar results have also recently been observed by other authors[3]). Pulses propagating along such a fiber are dispersively broadened, and the fiber is unable to support (bright) solitons. Nevertheless, we have found that even these temporally broadened pulses reinjected back into the master cavity can significantly improve the mode locking of the color-center laser in a dramatic way.

A schematic diagram of the coupled-cavity laser is shown in Fig. 1. The color-center laser alone, bounded by mirrors M_1 and M_0, typically produced pulses of ~15-psec duration and was tunable from 1.45 to 1.55 μm. The control cavity containing the fiber was formed by the output coupler M_0 of the color-center laser, beam splitter S_1, and a small dielectric mirror M_3 mounted on a piezoelectric translator (PZT). An elliptical-core fiber[4] (produced by the Andrew Corporation) was used to provide polarization-preserving and single-mode propagation at 1.5 μm. The relatively large germania content of the fiber (giving a Δn ~0.046) necessitates a small core (2.8 μm × 1.6 μm) in order to obtain propagation in a single mode, and this in turn produces a large waveguide dispersion, giving the fiber a net positive GVD. The average power coupled into the fiber was adjusted by a variable neutral-density (ND) filter.

With the control cavity unblocked and its length made equal to (or a multiple of) the master cavity, a significant shortening of the laser output pulses was seen to occur. An electronic stabilization scheme similar to that described in Ref. 2 was employed in order to provide for the correct relative optical phase matching between the pulses fed back from the fiber and those circulating in the master cavity. Once this stabilization loop was in operation, the output pulses from the composite cavity laser were very stable, with ~1% noise fluctuations. For a fiber length of 2.2 m the composite cavity laser produced pulses of ~1.1-psec duration, and the shortest pulses of 260 fsec (see inset of Fig. 3) were obtained with a fiber length of 24 cm. For the 2.2-m fiber, the laser produced stable pulses of constant duration for a power range of 10–25 mW within the fiber (measured just before M_3), and for shorter fiber lengths, the stability range shifted to

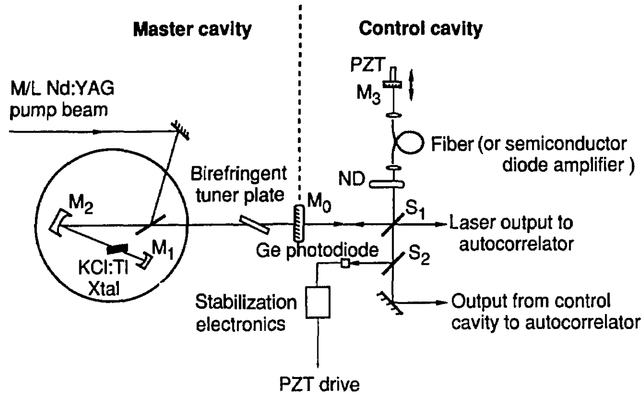

Fig. 1. Experimental arrangement of the coupled-cavity color-center laser. M/L, mode locked. Mirror reflectivities: M_1, M_2, M_3, ~100%; M_0, ~80%. Beam-splitter reflectivities: S_1, ~50%; S_2, ~30%.

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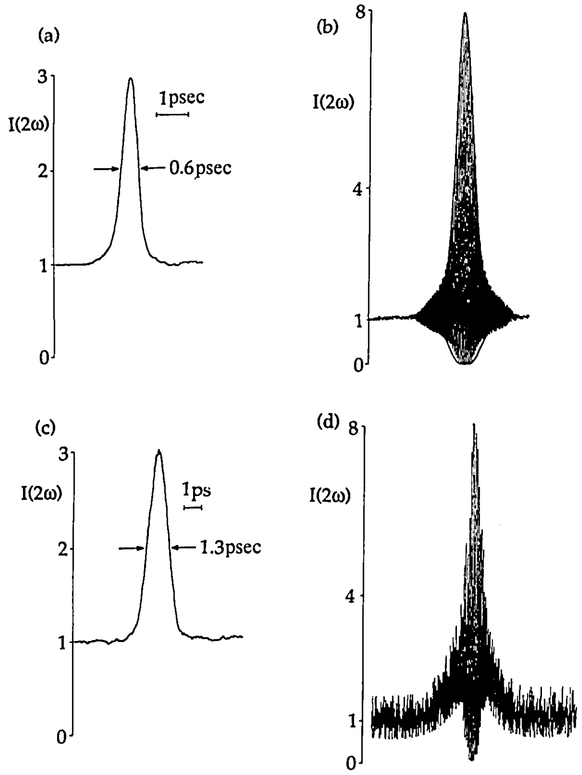

Fig. 2. Intensity and interferometric autocorrelation traces for pulses exiting the laser [(a) and (b)] and for pulses returning from the control fiber [(c) and (d)] with a fiber length of 55 cm. The fringes seen on the interferometric autocorrelations are not actual interference fringes but are due to sampling limitations on the digital oscilloscope.

slightly higher powers, approximately 30 mW for 24 cm. As can be seen from Fig. 1, we were also to monitor the pulses returning from the control cavity, and it was found that the duration of these pulses exceeded the duration of those exiting the laser for all the fiber lengths used. For the 2.2-m and 24-cm lengths, the fed-back pulse durations were 3.0 and 0.6 psec, respectively. Typical second-harmonic intensity and interferometric autocorrelation traces of the pulses are shown in Fig. 2 for a control fiber length of 55 cm. The laser output pulses had durations of 0.6 psec, whereas those fed back into the master cavity had durations of ~1.3 psec. The interferometric autocorrelation traces show a substantial difference between the two pulse trains. For the laser output [Fig. 2(b)] the pulses are well phase locked (as shown by the 8:1 contrast ratio); for comparison, a sech^2 fit to the envelope is also shown. There is a slight departure in the wings of the pulse, which may imply some excess frequency chirp, but it should be remembered that since the pulses are not solitons, there is no particular reason why the pulses should have sech^2 intensity profiles. The pulses returning from the control cavity [Fig. 2(d)] show a substantial linear frequency chirp due to the positive GVD of the fiber (indicated by the rising wings of the autocorrelation[5]), with only the central portion of the pulse being coherent. A similar structure was seen in all cases for these pulses. A plot of the pulse durations obtained from the coupled-cavity laser as a function of fiber length is shown as Fig. 3. In contrast to the soliton laser, where the output-pulse duration is proportional to the square root of the fiber length, no such simple relationship is observed here. It may also be inferred from this graph that an optimum fiber length exists for the production of the shortest output pulses. Owing to physical constraints of our experimental arrangement, further data around this minimum were not taken, but this would be required in order to establish the true existence of an optimum fiber length.

In our experimental configuration (Fig. 1), although the fiber itself provided positive GVD, any glass within the master cavity (e.g., Brewster-angled plates, an output coupler) may provide negative GVD and thereby lead to temporal compression of the frequency-chirped pulses. To verify that this was not the case and that negative GVD is not necessary for enhanced mode locking, a similar experiment was performed using a synchronously mode-locked LiF:F_2^+ color-center laser.[6] This laser produced pulses of typically 4-psec duration at a wavelength near 900 nm, where the material dispersion for glass is positive. A coupled-cavity arrangement was set up with a 2-m length of fiber, which was polarization preserving and monomode in the lasing wavelength region (Andrew Corporation fiber) similar to that previously described. With feedback from the control cavity, preliminary results have shown an observable pulse reshaping and narrowing, with the laser output pulses shortened to ~1 psec (Fig. 4).

The results described here seem to be in general agreement with the theoretical modeling characteristics reported recently by Blow and Wood.[7] They showed that pulses broadened by passage through a nonlinear element in the control cavity could still enhance the mode locking of a homogeneously broadened laser. The mechanism may be described as being due to the enhanced phase coupling involving additional longitudinal modes of the laser cavity (induced by the processes occurring within the nonlin-

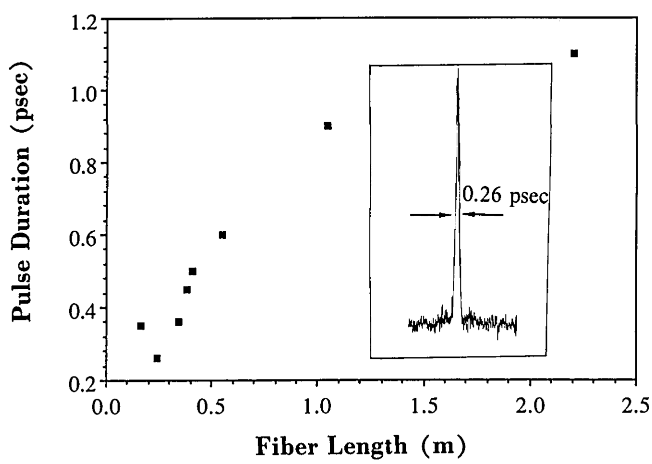

Fig. 3. Variation of the pulse duration from the coupled-cavity laser as a function of fiber length. The inset shows an autocorrelation trace of the 0.26-psec pulse with L = 24 cm.

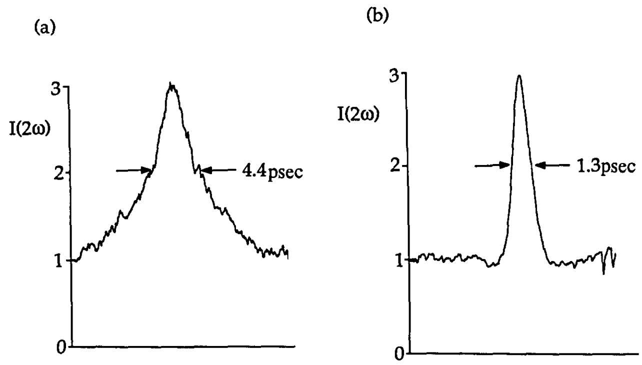

Fig. 4. Autocorrelation traces of the pulses obtained (a) from the LiF:F_2^+ laser alone and (b) with feedback from the control cavity for a fiber length of 2 m.

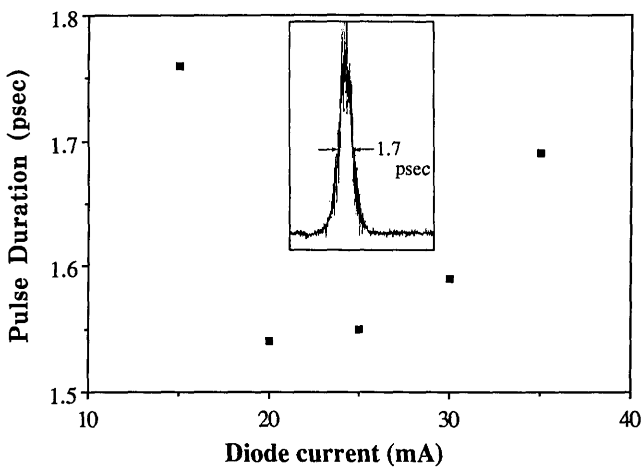

Fig. 5. Pulse duration versus drive current to the InGaAsP diode amplifier in the control cavity of the KCl:Tl color-center laser. The inset shows typical intensity autocorrelation of the output pulses for a 35-mA diode injection current.

ear element), thereby increasing the mode-locked bandwidth. Our experimental data are qualitatively consistent with this, but we did observe that the pulses reinjected into the master cavity had a broader bandwidth (owing to self-phase modulation) than the pulses exiting the laser. The role of saturable amplification in the control cavity has also been studied theoretically,[7] and we have evaluated this experimentally by using an InGaAsP semiconductor diode amplifier as the nonlinear element within a control cavity. The diode was operated at injection currents in the 10–35-mA range, and higher currents were not used in order to prevent lasing between one facet of the diode and mirror M_3 (Fig. 1). Our initial results showed pulse shortening to ~1.4 psec for a current of 20 mA. A plot of the pulse durations from the coupled-cavity laser as a function of diode current is shown in Fig. 5, where the inset is a typical autocorrelation trace of the output pulses for a current of 35 mA. Most recently, by optimization of the laser we have obtained pulses as short as 250 fsec, which is comparable with that of the fiber-based control cavity. In the diode-amplifier case, however, the laser has been observed to suffer regular dropouts, i.e., switching to the much broader color-center-laser pulses. The stabilization loop, although compensating for relatively slow cavity-length changes, was not able to eliminate these higher-frequency (~1-kHz) dropouts. It was also noted that the period of these could be varied by altering the length of the master cavity, and further study of these features is ongoing. The average power fed back into the master cavity was estimated to be less than 1 mW, yet, interestingly, this is still sufficient to produce the dramatic narrowing of the laser pulses reported here.

In summary, we have found that the existence of negative GVD in the control cavity of a color-center laser is not necessary to provide an enhanced mode locking of the laser. A semiconductor diode amplifier has also been demonstrated to produce a similar effect, in agreement with previous theoretical considerations.[7] Finally, it would seem from the results described here that actual soliton formation in the control cavity is a specific case of a more general phenomenon, whereby pulses reinjected into the master cavity from a control cavity containing a nonlinear element can completely dominate the mode-locking characteristics (i.e., coupled-cavity mode locking) of color-center lasers and will perhaps be applicable to other broad-bandwidth laser systems.

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