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Active mode locking of a neodymium-doped fiber laser using intracavity pulse compression

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Active mode locking of a Nd^{3+}-doped fiber laser with piezoelectrically induced Raman–Nath diffraction modulation is demonstrated. By using intracavity pulse compression, stable pulses of 2.4-psec length are generated at a wavelength of 1054 nm.

Since rare-earth-doped fibers were first manufactured,[1] steady progress has been achieved in obtaining ultrashort pulses from rare-earth fiber lasers. By using active mode-locking (AML) techniques, pulses as short as 20 psec have been generated in Nd^{3+}-doped fibers,[2] and pulse widths of 3.4 psec have been achieved in Er^{3+}-doped fibers.[3,4] This compares with pulse widths as short as 380 fsec that have been generated by passive mode locking of a bulk Nd^{3+}:glass laser[5] through self-starting additive-pulse mode locking[6] (APM). AML in bulk ND^{3+}:glass lasers has produced pulse widths of only 3.8 psec,[7] whereas a combination of AML with APM has produced pulse widths of 900 fsec.[8] Both AML techniques, however, suffer from large instabilities and are highly sensitive to cavity detuning.

We show here that active fibers allow one to overcome some of the instabilities inherent to AML bulk lasers and allow one to produce shorter pulses for given modulation indices. By employing chirp linearization, intracavity pulse compression, and a highly efficient diffraction modulator, we obtain stable pulses of 2.4-psec length at 1054 nm. The mode-locking technique is closely related to that of Ref. 3, where soliton compression was employed. Here we use a grating pair, as previously employed in synchronously pumped fiber Raman lasers.[9] The use of rare-earth ions as the active medium, however, permits an overall reduction of the pump powers and nonlinearities compared with a Raman system and leads to true bandwidth-limited pulses. Finally, guidelines for further optimization of this mode-locking technique are given, which demonstrates that rare-earth-doped fibers are a serious alternative to bulk short-pulse laser systems.[5,6]

We used standard germanosilicate fibers with small additions of P_2O_5 and doping levels of 200 and 6000 parts in 10^6 Nd^{3+} that emitted at 1054 and 1064 nm, respectively. The core diameters were 5 μm, the cutoff wavelengths were 0.75 and 1 μm, and the fiber lengths were l = 7.6 and 0.25 m, respectively. The short fiber had negligible birefringence, whereas the long fiber was slightly birefringent with a beat length of 8 cm at 1054 nm. From the waveguide data, the positive group-velocity dispersion (PGVD) in the fiber was calculated as $\beta_2 = d^2\beta/d\omega^2 = 30$ psec^2/km at 1054 nm.[10] Since the dopant host is mainly silica, the fibers exhibited strong inhomogeneous broadening, and therefore bandwidth-limiting elements were required in the cavity. Amplitude modulation was achieved by inserting a highly efficient piezoelectric modulator[7,11] into the cavity. Its effective modulation index[12] was measured as $\delta_l = 60P_{\mathrm{rf}}$, where P_{rf} is the absorbed rf power, at a wavelength of 1054 nm.[7] The experiments were performed at absorbed rf powers of 1 W, which gave modulation indices of ≈60 at an optical modulation frequency of 87 MHz. The device is highly advantageous compared with integrated-optic modulators, since it produces comparable modulation indices at virtually zero transmission loss, whereas typical integrated-optic devices have double-pass losses of 12 dB.[3] Intracavity pulse compression was performed by employing a polarizing holographic grating pair with 1700 lines/mm with a round-trip loss of ≈2 dB, giving an effective round-trip negative group-velocity dispersion (NGVD) of $\beta_g = -42$ psec^2/m grating separation.[13]

The optical arrangement for the mode-locking experiments is shown in Fig. 1. The cavity consisted of two highly reflecting mirrors (M1, M2) at the lasing wavelengths and a 50% beam splitter (BS) inserted for

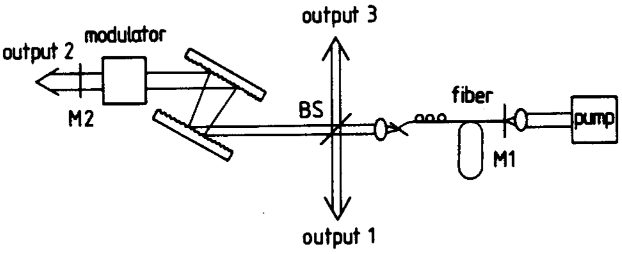

Fig. 1. Optical arrangement used for mode locking the fiber lasers.

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output coupling. Optionally the beam splitter was removed, and output coupling was performed by the modulator or launch mirror. An index-matching cell tilted near Brewster's angle and a single antireflection-coated lens were used to image the fiber end to a beam waist of 1 mm onto the modulator mirror. The Brewster angle was sufficient to ensure single-polarization-mode operation of the laser. Mechanical polarization manipulators[10] were then used in order to minimize losses due to depolarization in the fiber. The modulator mirror was in close contact with the modulator to minimize the active transmission loss. The fibers were pumped with 799- and 752-nm light from a krypton laser up to a power of 750 mW and a launching efficiency of 30%. With this arrangement the fiber lasers had a threshold of ≈15-mW launched power. The total output power saturated at a level of ≈14 mW for launched powers greater than ≈120 mW. The unsaturated slope efficiency was ≈12%. Under mode-locked operation the output power remained essentially unchanged.

Initially the modulator was tested without the grating pair with the short fiber length to minimize dispersion. With an intracavity étalon with an effective bandwidth of 4.3 nm,[12] we obtained near sech^2 pulses of 7.7-psec width FWHM as delivered from curve-fitting routines. The pulse length was found to be approximately constant for output powers ranging from 3 to 12 mW; however, owing to the extreme sensitivity of the pulse shape on cavity misalignment, an exact reproduction of cavity parameters for different output powers was not possible. The pulses were stable up to maximum launched powers of ~50 mW; at higher launched powers small fluctuations in the pump power impaired stable mode locking. Tolerable cavity-length detuning was of the order of <1 μm. Following the classical analysis of Kuizenga and Siegman,[12] our setup should have produced pulses of 13-psec width. This approximate reduction in pulse length by a factor of 2 may be attributed to self-phase modulation in the fiber.[14,15]

Mode locking under the condition of intracavity pulse compression was performed with the 7.6-m-long fiber in order to linearize the positive chirp produced by self-phase modulation and PGVD in the fiber.[13] As a result we had seven pulses simultaneously present in the cavity. We chose a grating separation of $d = 9.4$ cm, which gave a round-trip NGVD of $B_g = \beta_g d = -3.9$ psec^2 compared with the PGVD of $B_2 = \beta_2 2l = +0.46$ psec^2 that results from fiber dispersion. The pulse shapes were monitored at four points in the cavity. By use of the beam splitter we measured the pulses emerging from the fiber (output 1) and going into the fiber (output 3) and also the pulse at the modulator mirror (output 2) and at the launch mirror. The pulses at the launch mirror and the pulses from outputs 1 and 3 had approximately the same width and were a factor of 1.3 longer than the pulses at the modulator mirror. This indicates that the grating pair overcompensates the chirp generated in the fiber. For a total cw output power of 14 mW, we obtain a peak pulse output power of 50 W. The corresponding intracavity power of ≈70 W gives rise to a round-trip self-phase-modulation-induced phase shift of ≈3π in the fiber. The autocorrelation trace of the pulse at the modulator mirror is shown in Fig. 2. In the absence of an exact theoretical description of the pulse-forming process we tried several fitting routines on the pulse shapes. Both sech^2 and symmetric two-sided exponential fits (ste) produced acceptable results, delivering pulse widths of 2.4 and 1.5 psec, respectively. However, the pulse tails favored ste pulses, an indication of exponential pulse wings. A measurement of the mode-locked pulse spectrum is shown in Fig. 3, giving a FWHM width of ≈0.53 ± 0.1 nm with a time–bandwidth product of 1.1 ± 0.2 and 1.4 ± 0.2 times the bandwidth limit for sech^2 and ste pulses, respectively. The reproducible single spectral side lobe observed in Fig. 3 may be attributed to cross-phase-modulation-induced modulational instability,[16] where the asymmetric side lobe is due to the filtering action of the fiber birefringence.

We believe the pulse width to be mainly limited by the linewidth-narrowing property of the fiber birefringence, since in conjunction with the polarizing gratings it produces double-pass transmission windows of only 5-nm bandwidth FWHM in reflection. The pulse width should become shorter using high- or low-birefringence fibers. In our fiber the birefringence

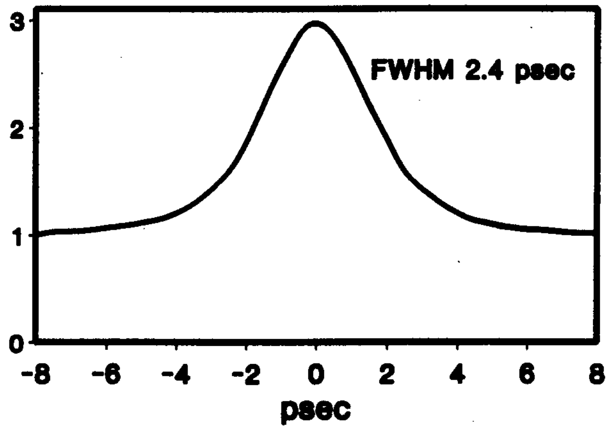

Fig. 2. Autocorrelation trace of generated pulses at output 2. The FWHM, assuming sech^2 pulses, is 2.4 psec.

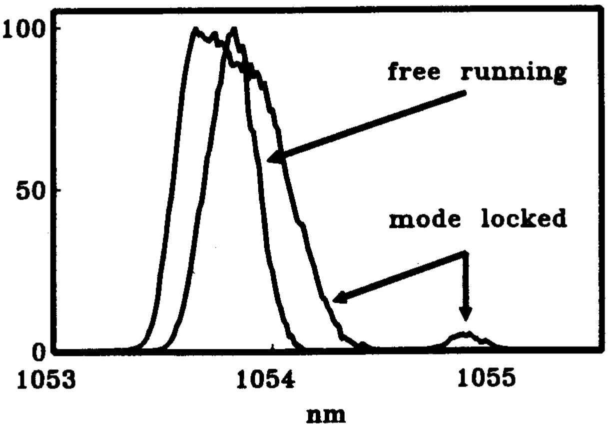

Fig. 3. Free-running and mode-locked spectra (not to scale) of the mode-locked pulses showing a single reproducible spectral side lobe.

could be used to tune the laser over a range of 15 nm by adjusting the mechanical polarization manipulators. In contrast to pure AML, the pulse length was not critically dependent on laser parameters such as laser power, modulation index, and cavity detuning. In fact the cavity could be detuned by several tens of micrometers without a noticeable effect on pulse length, leading to stable pulses for periods of hours. No attempts were made to optimize the fiber length. However, it is instructive to compare our results with those of Ref. 13. Our intracavity power and pulse length yield a soliton order of 7 and a soliton period of 100 m.[9] By assuming optimum pulse compression for unchirped pulses of 2.4 psec FWHM, the optimum grating separation is calculated as 12 cm, and the optimum fiber length is calculated as 20 m. This is three times longer than our active fiber length and shows that shorter pulses should be expected by a reduction in overall NGVD. However, owing to the bandwidth-limiting property of the fiber birefringence, no noticeable reduction in pulse width could be seen when reducing the grating separation by as much as a factor of 2. By following the design criteria from Ref. 13, shorter pulses could be supported by shorter fiber lengths, which would equally reduce higher-order nonlinear effects. However, an optimum shorter fiber length has to ensure that the nonlinear dispersion from the active medium is still small compared with the (essentially linear) host material dispersion in order to ensure that the generated chirp may be properly compensated by the grating pair. On the other hand, stable longer wavelength-tunable pulses (currently of great interest in optical soliton telecommunications) could be conveniently produced by increasing the fiber birefringence.

In summary, we have described a novel cavity design for mode locking fiber lasers. The scheme can be readily extended to fiber lasers operating at other wavelengths. Under appropriate conditions lossless NGVD-producing elements such as fiber gratings or prism pairs could be employed. The cavity design is ideally suited for cladding pumping of Nd- or Er/Yb-doped fibers with semiconductor or YAG lasers, respectively, or pump multiplexing with a series of couplers. This should give rise to a high-power system producing stable short pulses by AML, serving as an attractive alternative to passive APM systems. In addition the mode-locking technique could find applications in future soliton-based optical telecommunication.

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