60-fsec pulse generation from a self-mode-locked Ti:sapphire laser

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Pulses having durations as short as 60 fsec have been directly generated by a self-mode-locked, dispersion-compensated Ti:sapphire laser. By using an extracavity fiber–prism pulse compressor, pulse durations as short as 45 fsec have been obtained.

Titanium:sapphire ($Ti:Al_2O_3$) has been shown to be an attractive gain medium for laser operation in the near-infrared spectral region. Its broad gain bandwidth means that in addition to a large tuning range it is especially well suited to ultrashort-pulse generation and amplification. $Ti:Al_2O_3$ lasers have been mode locked by using a variety of techniques, including synchronous pumping,[1,2] acousto-optic mode locking,[3–5] passive mode locking,[6] injection seeding,[7] and coupled-cavity (also referred to as additive-pulse or interferential) mode locking,[8,9] in which the mode-locking process may be self-starting.[10]

To date the shortest pulses reported from $Ti:Al_2O_3$ lasers have had durations of 300 fsec and have been generated using injection-seeding techniques.[7] By using a nonlinear external cavity, pulses as short as 800 fsec have been directly generated from an actively mode-locked coupled-cavity laser.[8] By using a diffraction grating pair outside the laser cavity for dispersion compensation, the output from a self-starting coupled-cavity $Ti:Al_2O_3$ laser has been compressed to 200 fsec.[10] With intracavity dispersion compensation, pulses as short as 150 fsec can be directly produced.[9]

In this Letter we present results for a self-mode-locked $Ti:Al_2O_3$ laser from which pulses having durations of 2 psec can be generated. By using an intracavity two-prism sequence for dispersion compensation,[11] the pulse durations can be directly reduced to less than 100 fsec at average laser powers in excess of 400 mW. A further reduction in pulse duration to less than 50 fsec can be achieved by using an extracavity fiber–prism pulse compressor, which incorporates four high-dispersion ZnSe prisms in a configuration that provides adjustable anomalous group-velocity dispersion (GVD).

The self-mode-locked $Ti:Al_2O_3$ laser, illustrated schematically in Fig. 1, is a modified Spectra-Physics Model 3900 system. The main laser cavity, consisting of mirrors M_0 to M_3, was extended to between 1.5 and 2.0 m, with the 20-mm-long Brewster-angled $Ti:Al_2O_3$ gain medium placed in the center of the cavity. The plane output coupler M_0 had a transmission of approximately 3.5% over the 850–1000-nm spectral region, and the spherical mirrors M_1 and M_2 ($r = 10$ cm) were highly reflecting over this wavelength range and highly transmitting for the 488–514-nm pump wavelengths. The pump laser was a Spectra-Physics Model 2030 argon-ion laser that operated on all lines in the visible at as much as 20 W of power in a TEM_{00} mode. The pump beam passed through a periscope arrangement to rotate the plane of polarization by 90° and was focused into the $Ti:Al_2O_3$ gain medium by spherical mirror M_4, which had a radius of curvature of 22.8 cm. The prisms P_1 and P_2 were made from high-dispersion SF14 glass and were Brewster angled for minimum deviation at approximately 850 nm. They constituted the intracavity double-prism sequence for dispersion compensation, as shown in the inset of Fig. 1. For tuning purposes the standard Spectra-Physics three-plate birefringent filter was replaced by either a single-plate birefringent filter or by a variable-aperture slit placed between P_2 and M_3.

The mode-locked pulses from the laser were recorded by using a real-time autocorrelator that provided both intensity and interferometric autocorrelation data. A fast photodiode and oscilloscope combination was used to monitor the pulse sequence, and the spectral characteristics of the pulses were recorded with a 25-cm scanning monochromator that had a resolution of approximately 0.8 nm.

With the cavity arrangement shown in Fig. 1, the pump power threshold for cw laser oscillation was approximately 1 W, and at a pump power level of 6 W the output power of the $Ti:Al_2O_3$ laser was typically ~500 mW. In this configuration the laser could be made to

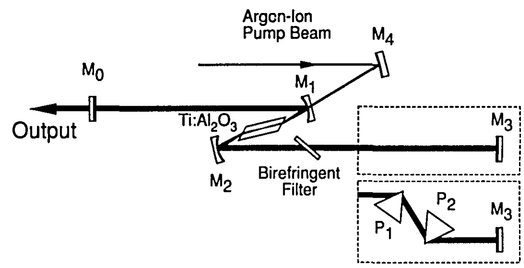

Fig. 1. Schematic of the cavity configuration for self-mode-locked $Ti:Al_2O_3$ laser. The inset shows the intracavity prism sequence for dispersion compensation.

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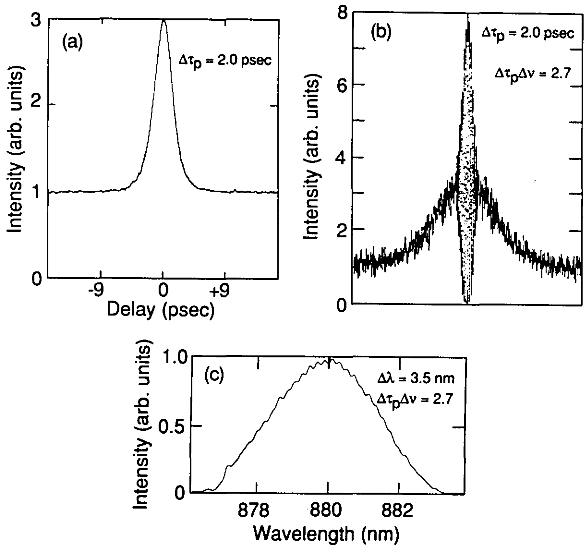

Fig. 2. (a) Intensity and (b) interferometric autocorrelation traces and (c) the associated spectrum for the mode-locked $Ti:Al_2O_3$ laser.

self-mode lock by simply realigning the cavity slightly using one or both of the end mirrors. This realignment resulted in a reduction of ~40% in average output power, so that for 6 W of pump power the average output was ~300 mW and the threshold for laser oscillation increased to approximately 2 W. The output beam profile also changed from the entirely TEM_{00} mode pattern obtained with optimum alignment to a beam that had ~70% of the average power concentrated in the fundamental mode. The remaining 30% of the laser output power was in a low-order transverse mode such as TEM_{05}.

With an appropriate cavity alignment self-mode-locked operation could be induced by applying some external perturbation, for instance, tapping one of the resonator mirrors. Occasionally the mode-locking process was observed to start spontaneously, although any sudden physical shock could also start or stop mode-locked operation. For a pump power of 8 W the average mode-locked output power was approximately 450 mW. The range of pump powers over which the laser would self-mode lock was found to be between ~4 and 12 W. Outside this range the laser would revert to cw un-mode-locked operation. To date all attempts to eliminate the higher-order transverse modes, by using an intracavity aperture, for example, have also resulted in the collapse of the mode-locked output. With no dispersion compensation the shortest pulses were obtained with the thickest available birefringent filter (1.6 mm) in the cavity, and these had durations of 2.0 psec as typified by the intensity autocorrelation trace in Fig. 2(a) ($sech^2$ intensity profiles are assumed). The laser was also operated with a 0.8-mm birefringent filter, and in this case the pulse duration increased to ~12 psec. Similarly, with no intracavity tuning element the pulse duration again increased to ~16 psec.

When the laser was mode locked its tuning range extended approximately from 845 to 950 nm. The lower value is a result of reaching the low-wavelength limit of the optics, and any attempts to tune below this wavelength either caused the laser oscillations to cease or, more frequently, the wavelength to jump back to that allowed by the neighboring order of the birefringent filter. Beyond the upper end of the mode-locked tuning range the laser continued to oscillate but in an un-mode-locked fashion until eventually laser threshold was not established. Within this wavelength range the laser could be tuned smoothly and continuously while the mode-locked output was maintained, with the shortest pulses being generated near the 870-nm region. This is in contrast to other types of mode-locked $Ti:Al_2O_3$ lasers, where the range over which the laser may be continuously tuned is restricted by, for example, the effective change in length owing to the dispersion of an optical fiber in an interferometrically matched external cavity. When the shorter-wavelength optics, covering the 700–850-nm spectral region, were used, mode-locked operation could also be obtained between 750 and 850 nm.

Reference to the pulse spectrum shown in Fig. 2(c) indicates that the mode-locked pulses generated from the laser have a very large associated duration–bandwidth product ($\Delta\tau_p\Delta\nu = 2.7$). This implies that the pulses are strongly frequency chirped, and this is further confirmed by the interferometric autocorrelation trace shown in Fig. 2(b), where the loss of coherence in the wings is characteristic of frequency-chirped pulses.[12] This frequency chirp must originate from within the main laser cavity and is due primarily to the presence of self-phase modulation (SPM) and GVD within the $Ti:Al_2O_3$ gain medium.

With the two-prism sequence described above and shown in the inset of Fig. 1, the pulse-broadening effects can be overcome. The threshold for laser oscillation and the average output power did not change significantly with the insertion of the prism sequence. The shortest pulses were then generated when the birefringent filter was removed from the laser cavity. The optimum prism separation, for which these short-

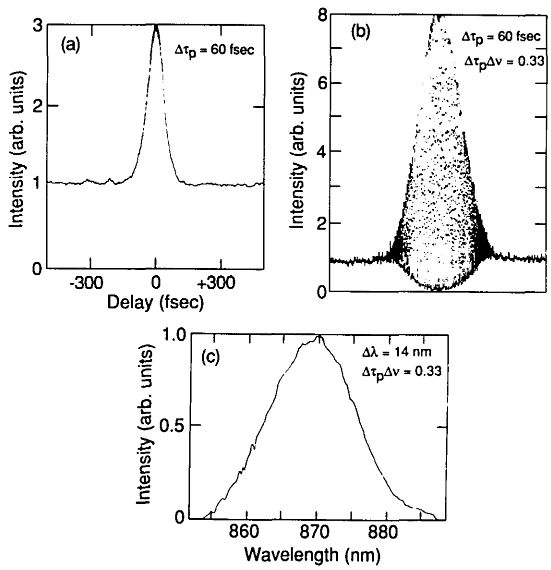

Fig. 3. (a) Intensity and (b) interferometric autocorrelation traces and (c) the associated spectrum for the mode-locked $Ti:Al_2O_3$ laser.

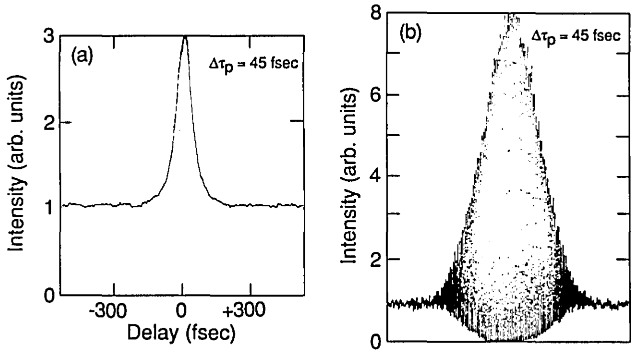

Fig. 4. (a) Intensity and (b) interferometric autocorrelation traces for the mode-locked Ti:Al_2O_3 laser pulses after extracavity pulse compression.

est pulses were produced, was found to be 35 cm. Under these conditions pulses having durations as short as 60 fsec were generated. For a pump power of 8 W the average output power was 450 mW, and thus for a typical cavity period of 12 nsec this represents a peak pulse power of 90 kW.

Typical autocorrelation and spectral data associated with the shortest pulses are presented in Fig. 3. It is clearly evident from the duration–bandwidth product of 0.33, which is close to the Fourier-transform limit of 0.32, that the pulses are essentially free from excess frequency chirp. This is confirmed by the interferometric autocorrelation trace where the fringe visibility extends into the wings of the pulse. For the dispersion-compensated cavity the laser output was still multimode, but the percentage of the average power in the fundamental mode was generally much higher at ~99%.

Self-mode-locked operation could be obtained for cavity lengths that ranged from approximately 1.5 to 2.0 m, which corresponds to a cavity frequency range of 100–75 MHz. Outside this range only a cw unmode-locked output could be obtained, and the resonator did not exhibit multitransverse-mode operation. Within the 75–100-MHz latitude the cavity frequency could be continuously and smoothly varied while mode-locked operation was retained, and there was no evidence that the mode-locked output had any particular dependence on the length of the resonator.

A potential qualitative understanding of the self-mode-locking mechanism can be provided if the two modes within the resonator interact in a manner similar to that of the modes in the main and external cavities of a mode-locked, dispersion-compensated coupled-cavity Ti:Al_2O_3 laser.[9] Thus the operation of the laser can be regarded as a simplified version of coupled-cavity mode locking in which the Ti:Al_2O_3 crystal provides both the gain and the nonlinearity. Further checks on the validity of this proposed interpretation are the subject of ongoing research.

A further reduction in pulse duration could be obtained by using an extracavity fiber–prism pulse compressor. This consisted of a length of optical fiber, chosen so that the GVD linearized the SPM-induced frequency chirp on pulses that had a given peak power. The linearly chirped pulses could then be compressed by using adjustable anomalous dispersion provided by a grating pair or, as in this case, a four-prism sequence. The prisms were preferred to the grating pair because higher transmissions of ~85% could be achieved. For an average output power of 300 mW and pulse durations of 90 fsec and assuming a 50% coupling efficiency into the fiber, the correct length of fiber to linearize the frequency chirp is calculated to be approximately 7 cm, and the optimum prism separation is approximately 10 cm. With the pulse compressor optimized, pulse durations as short as 45 fsec were obtained, with average and peak powers in excess of 100 mW and 25 kW, respectively. Representative autocorrelation traces for these pulses are shown in Fig. 4.

In summary, we have demonstrated what is to our knowledge the first self-mode-locked Ti:Al_2O_3 laser that is capable of producing pulses with durations as short as 2.0 psec. We have also, for the first time to our knowledge, used intracavity dispersion compensation in a mode-locked Ti:Al_2O_3 laser to produce pulse durations as short as 60 fsec and peak powers of 90 kW. We believe that these are the shortest, highest-peak-power pulses that have been directly generated by a mode-locked Ti:Al_2O_3 laser to date. By using an extracavity fiber–prism compressor and utilizing high-dispersion ZnSe prisms, pulses as short as 45 fsec have been produced.

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