The large gain bandwidth of titanium-doped sapphire (Ti:Al₂O₃), which permits both an extensive tuning range and the capability of ultrashort-pulse generation, has led to its becoming an attractive laser material. As such, Ti:Al₂O₃ lasers are likely to replace colliding-pulse mode-locked dye lasers as standard sources of femtosecond pulses in many applications such as time-resolved spectroscopy.

Recently ultrashort pulses have been produced from Ti:Al₂O₃ lasers by using a variety of techniques, including active mode locking, passivity mode locking with a saturable absorber, passive mode locking with a glass filter, additive-pulse mode locking, coupled-cavity mode locking with a multiple quantum well, synchronous pumping, passive mode locking with nonlinear solid-state modulators, and self-mode locking. Spence et al. directly produced pulses of 60-fs duration from a dispersion-compensated self-mode-locked laser, although the output was not TEM₀₀ as high-order spatial modes were required for mode-locked operation. The mode locking was also critically dependent on a misalignment of the cavity. It has recently been shown that high-order spatial modes are not necessary for self-locking and that self-focusing inside the Ti:Al₂O₃ gain medium can be utilized to generate sub-100-fs, transform-limited pulses in a TEM₀₀ mode. We have previously reported the generation of picosecond pulses from a Ti:Al₂O₃ laser coupled to an external cavity containing a moving mirror whereby we proposed that the moving mirror caused Q switching that induced the nonlinearity in the gain medium to initiate mode locking. Intensity-dependent polarization rotation through the Kerr nonlinearity or self-focusing was thought to be responsible for sustaining the mode-locked pulses. Gabetta et al. have recently shown that the nonlinearity required to generate mode-locked pulses need not necessarily be confined to the gain medium by using modular optical devices at the ends of their cavities to introduce self-focusing or polarization rotation.

It is probable that in the wide variety of mode-locking techniques demonstrated with Ti:Al₂O₃ lasers so far (e.g., Refs. 1, 7, and 9), the same mechanisms based on the optical Kerr nonlinearity inside the Ti:Al₂O₃ rod have been responsible in each case for the ultrashort-pulse formation, once a sufficiently intense fluctuation has been introduced, as hypothesized in Ref. 11. This fluctuation can be induced by a variety of means, e.g., with transverse-mode beating, a synchronously mode-locked pumping source, or a moving mirror. Owing to this non-self-starting, one drawback of self-mode-locked systems has been the tendency for the mode locking to be sensitive to mechanical shocks and hence to fall back, periodically into cw operation. Keller et al. showed that a multiple-quantum-well device in a coupled cavity would maintain a continuously mode-locked output. Our previous results with a moving-mirror external cavity produced picosecond pulses that were many times transform limited and for which dropout occurred in the pulse train at the zero-velocity position of the moving mirror. We now show that a moving mirror, coupled to a Ti:Al₂O₃ resonator similar to that of Negus et al., can start and maintain cw self-mode locking to produce transform-limited sub-100-fs pulses.

The experimental configuration is shown in Fig. 1. The Ti:Al₂O₃ laser consisted of a standard, astigmatically compensated cavity containing a 20-mm-long Ti:Al₂O₃ Brewster-angled rod, a pair of high-dispersion SF10 glass Brewster prisms, and, optionally, a vertical slit aperture. The Ti:Al₂O₃ rod had a nominal concentration of 0.1% of Ti³⁺ ions by weight. All the mirrors had single-stack dielectric coatings, and the radius of curvature of the folding mirrors M1 and M2 was 10 cm. The transmission of M3 and M4 at 800 nm was 3.5% and <1%, respectively. The laser was pumped by all-lines output from a small-frame argon-ion laser. A single-plate birefringent filter could be inserted for tuning purposes. The external cavity comprised three low-quality aluminum-coated mirrors. Mirror M5 was mounted on a Bruel and Kjaer Mini Shaker (Model 4810) and was vibrated at −25 Hz at low amplitudes. To utilize self-focusing in the gain medium, we constructed the cavity such that mirror M2 was closer to the cavity waist inside the rod than mirror M1 (which was set for collimation of the beam). With this asymmetric arrangement, the resonator is more stable (i.e., there is lower loss) for applications such as time-resolved spectroscopy.

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An external cavity coupled to a dispersion-compensated, self-mode-locked Ti:sapphire laser is shown to maintain cw mode locking to produce pulses as short as 47 fs. The same cavity arrangement is also shown to generate transform-limited pulses of 2-ps duration in the regime of linear external cavity mode locking.

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a high-intensity self-focused mode than for a low-power one (i.e., the self-focusing brings the laser beam back into collimation), and thus an intensity-dependent loss mechanism is present.\cite{footnote10}

The cw lasing threshold of the single-cavity Ti:Al$_2$O$_3$ laser was $-1$ W of absorbed pump power. Mode-locked operation started at $-3$ W above the cw threshold when a suitable perturbation was imparted to the cavity (e.g., by translating one of the end mirrors along the laser axis or lightly tapping a cavity element) or when the external cavity with the moving mirror was employed. With just a single cavity, the mode locking was sustained until a subsequent disturbance stopped the process. Unlike with the laser of Spence et al.,\cite{Spence1991} misalignment of the cavity to give a multimode output was not necessary. We observed strong thermal lensing in our Ti:Al$_2$O$_3$ rod, but stable mode locking with a good beam profile was obtained nonetheless.

Self-mode-locked operation was possible with or without the prism sequence. Pulses of 8-ps duration were produced without dispersion compensation. However, femtosecond pulses could be readily generated by the insertion of the prism pair. These pulses were quite unstable until the vertical slit was placed in close proximity to the output coupler M3. The slit stabilized both the pulse amplitude and the pulse width, although the output power dropped by about 40% to $-110$ mW at 5.5-W pump power. The pulse widths were measured using standard collinear non-background-free autocorrelation using a 100-μm-thick LiIO$_3$ crystal. All spectra were recorded using a Monospek 1000 1-m spectrograph with a resolution of less than 0.1 nm. Tunable operation of the laser was limited simply by the reflectivity of the cavity mirrors.

The optimum prism separation was found to be 35 cm. The variation of the pulse width and bandwidth with glass path for this separation is shown in Fig. 2. Pulses as short as 47 fs were produced from the self-mode-locked laser. An autocorrelation trace and the corresponding spectrum for such a pulse are shown in Figs. 3(a) and 3(b). The time-bandwidth product of 0.39 is close to the transform limit for sech$^2$ pulses.

Truly cw mode-locked output occurred when the external cavity was feeding back into the main cavity with mirror M5 moving sinusoidally at 25 Hz for amplitudes of 0.5 mm. The cavity length matching was found to be noncritical,\cite{footnote12} and the length of the external cavity was approximately equal to the main cavity length (to within a few millimeters). The repetition rate of the pulses was determined purely by the main laser cavity. Two modes of operation were possible with the external cavity. In general, with external cavity feedback, contiguous pulses trains as in Ref. 12 could be generated, and the shortest pulses produced with this configuration were 1.2 ps (Fig. 4). These pulses are shorter than the previously reported linear external cavity results of 5 ps (Ref. 12) owing to the improved control of the intracavity dispersion. For one particular alignment of the external cavity, however, truly cw (dropout-free) self-mode-locked operation that produced femtosecond pulses was stably maintained for as long as the external cavity was coupled to the Ti:Al$_2$O$_3$ laser. In this mode of operation, the only amplitude modulation observed in the laser out-

![Fig. 1. Schematic of the cavity configuration.](image1)

![Fig. 2. Pulse width and bandwidth variation with the intracavity glass path.](image2)

![Fig. 3. (a) Intensity autocorrelation and (b) associated spectrum for the self-mode-locked Ti:Al$_2$O$_3$ laser.](image3)

![Fig. 4. (a) Spectrum and (b) intensity autocorrelation for a pulse produced with linear external cavity feedback. These autocorrelations represent an average over the repetitive pulse evolution.](image4)
put directly correlated with that of the pump laser. Once femtosecond pulse operation was established, the external cavity could be blocked without the overall characteristics of the output being affected. These two operating regimes, while both driven by the optical Kerr effect in the Ti:Al₂O₃ rod, thus appear to be distinguished by the alignment of the external cavity. Simple variation of the intensity of the feedback signal, however (e.g., by using neutral-density filters), did not switch the operation from the picosecond to the femtosecond regime. Once in the femtosecond regime, the laser self-started in that mode of operation. For the longer-pulse regime, the linear external cavity appears to initiate the mode locking and then suppress it for each cycle of the moving mirror. The recent research by Haus and Ippen⁴ may help to explain this observation.

For the shorter-pulse regime, a critical degree of feedback is achieved that perhaps produces a weaker initial fluctuation in the intracavity radiation that can still serve to start the self-mode locking. The feedback is, however, not sufficiently strong to bring about the demise of the established pulse trains.

Figure 5 shows an interferometric autocorrelation of a 53-fs self-mode-locked pulse, and it is evident from the clear fringe visibility in the wings of the pulse that no excess bandwidth exists. We were able routinely to produce transform-limited pulses of ~50-fs duration. By increasing the amount of positive group-velocity dispersion of the cavity, bandwidths exceeding 24 nm were generated from the self-mode-locked laser (see Fig. 6). Such bandwidths are able to support pulses of ~28 fs at 800 nm. The characteristic two-peaked spectrum shown in Fig. 6 suggests that the spectrum is straddling a point of zero dispersion. Hence, not all of the spectral content is in the net negative group-velocity-dispersion region and thus able to participate in solitonlike pulse formation. In our cavity, only second-order dispersion compensation is provided, and it is likely that higher-order dispersion compensation will be required for transform-limited sub-30-fs pulse formation.

In summary, we have routinely generated transform-limited pulses of ~50-fs duration directly from a self-mode-locked Ti:Al₂O₃ laser. These pulses are, to our knowledge, the shortest produced using this technique. We have used an external cavity with a slowly moving mirror to eliminate any dropouts in the pulse train. This is a simple and inexpensive method of starting and maintaining the self-mode-locked operation. The exact alignment of the external cavity determines whether self-mode locking or linear external cavity mode locking regime is established. Neither regime shows any degradation in the spatial mode of the laser.

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