Ultralow-threshold Kerr-lens mode-locked $Ti:Al_2O_3$ laser

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An ultralow-threshold Kerr-lens mode-locked $Ti:Al_2O_3$ laser achieved by use of an extended cavity design is demonstrated. Mode-locking thresholds as low as 156 mW are achieved. Pulses with durations as short as 14 fs and bandwidths of >100 nm with output powers of ~15 mW at 50-MHz repetition rates are generated by only 200 mW of pump power. Reducing the pump power requirements to a factor of 10× less than required by most conventional Kerr-lens mode-locked lasers permits inexpensive, low-power pump lasers to be used. This will facilitate the development of low-cost, high-performance femtosecond $Ti:Al_2O_3$ laser technology.

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Kerr-lens mode-locked (KLM) $Ti:Al_2O_3$ lasers can generate extremely short pulses with broad bandwidths and have widespread applications in ultrafast studies, materials processing, and biomedical imaging.[1] A standard KLM laser operating with a 5-W pump can produce output powers of 500 mW with 5 nJ of pulse energy. With intracavity prisms to compensate for dispersion, pulse durations as short as ~10 fs and bandwidths of >100 nm can be achieved.[2,3] Even shorter pulse durations, approaching ~5 fs, are possible with double-chirped mirrors (DCMs) that compensate for intracavity dispersion over large bandwidths.[4,5]

One disadvantage of femtosecond $Ti:Al_2O_3$ lasers is their high cost. This cost severely limits widespread use of femtosecond lasers. The cost of $Ti:Al_2O_3$ lasers is strongly dependent on the pump power requirements of the lasers. Diode-pumped, solid-state lasers generating 5 W of power are extremely expensive, whereas those that generate several hundred milliwatts can be more than five times lower in cost. Therefore the development of ultralow-threshold femtosecond $Ti:Al_2O_3$ lasers can significantly reduce the cost of femtosecond laser technology. Previous studies demonstrated low-threshold $Ti:Al_2O_3$ lasers with a KLM starting threshold of 500-mW pump power and sustained mode-locked operation below 400-mW pump, generating 18-fs pulses with 66-nm bandwidths.[6]

Here we report the development of an ultralow-threshold mode-locked $Ti:Al_2O_3$ laser. Pumping with low power reduces the total output power and may result in reduced pulse shaping strength as a result of Kerr-lens mode locking. However, because the pulse energy is given by the average power divided by the pulse repetition rate, increasing the cavity length increases the pulse energy.[7,8] This increased pulse energy permits high-performance KLM operation even at low pump powers. Long cavities also decrease the spot size of the laser mode in the laser crystal, resulting in lower pump thresholds. We report what is, to our knowledge, the lowest threshold achieved to date for a KLM $Ti:Al_2O_3$ laser. Stable mode locking can be initiated and sustained with as little as 156 mW of incident pump power. Pulse durations of 14 fs are generated with 91-nm bandwidths and 16-mW output power at a 50-MHz repetition rate for 200-mW pump power. At the same pump power, output spectra with bandwidths of approximately 100 nm can also be generated but with increased pulse duration. This ultralow-threshold laser reduces the pump power requirement to be a factor of 10 less than required by most conventional KLM lasers, facilitating the use of low-cost, low-power pump lasers. Ultralow-threshold lasers promise to reduce significantly the cost of femtosecond technology and permit its applications in many fields.

Figure 1 shows a schematic of the ultralow-threshold KLM $Ti:Al_2O_3$ laser. The pump source is a frequency-doubled, diode-pumped Nd:vanadate laser. The cavity is an astigmatically compensated, X-folded configuration with a 2-mm-thick $Ti:Al_2O_3$ laser crystal that has an absorption coefficient $\alpha = 5.0\ \mathrm{cm}^{-1}$. The focusing mirrors have 7.5-cm radii of curvature and transmit greater than 95% of the pump beam at 532 nm. The output coupler has a transmission of ~1% from 700 to 900 nm. All the mirrors are commercially available Bragg stacks with

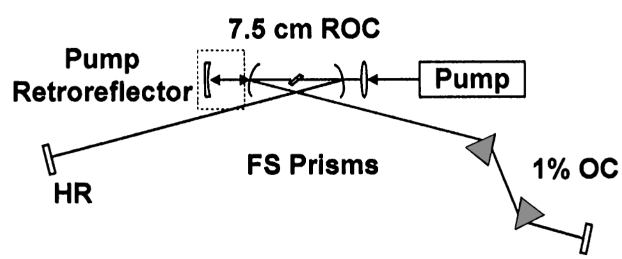

Fig. 1. Schematic diagram of the ultralow-threshold $Ti:Al_2O_3$ laser. The pump lens has a 50-mm focal length, and the folding mirrors have 7.5-cm radii of curvature (ROC). The cavity is an astigmatically compensated X design, with arm lengths of 130 and 162 cm for the highly reflecting (HR) arm and the prism arm, respectively. A pair of fused-silica (FS) prisms separated by 45 cm is used for compensating and tuning intracavity dispersion. The output coupler is ~1%. The Kerr-lens mode-locking threshold is 156 mW of pump power.

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low dispersion. Because this laser uses commercially available mirrors and intracavity prisms rather than double-chirped mirrors for dispersion compensation, third-order dispersion limits the pulse duration and bandwidth. Previous studies showed that third-order dispersion is minimized when the laser wavelength is shifted to longer wavelengths.[9] Our mirror set was chosen to shift the laser wavelength to be centered at approximately 840 nm. Intracavity dispersion compensation is accomplished with a pair of fused-silica Brewster prisms separated by 45 cm. We tune the dispersion by varying prism insertion.

To achieve high-performance KLM operation at low thresholds we extend the laser cavity, which has a 50-MHz repetition rate. The arm lengths of the cavity are 130 cm for the straight arm and 162 cm for the prism arm. In addition to increasing the pulse energy by a factor of 2 compared with that of the standard 100-MHz cavity configuration, the increased arm lengths also reduce the laser mode size in the crystal to ~ 8-μm radius. Increasing the pulse energy by cavity length scaling permits stronger Kerr-lens mode locking and shorter pulses at low pump powers. The tight focusing of the laser mode reduces the laser threshold.

To utilize the pump power more efficiently, we employ a double-pass pump configuration. The pump is focused with a 50-mm focal-length, antireflection-coated, achromatic lens. The unabsorbed pump power transmitted through the laser crystal is retroreflected by a curved dielectric mirror. Figure 2 shows the relationship between pump power and output power for mode-locked operation as well as for single- and double-pass cw operation. Because the crystal absorbs only $\sim 63\%$ of the light on the first pass and the laser operates close to threshold, this second pass of the pump gives a factor of ~ 2 increase in cw output power. All pump powers quoted are the incident powers measured before the pump lens.

The laser can be set for KLM operation by adjustment of the curved mirror separation to the inner boundary of the outer stability region. Kerr-lens mode locking is started by rapid translation of the end mirror that is mounted on a precision rail to induce intensity fluctuations. It can be started and sustained with pump powers as low as 156 mW, where the laser generates 9 mW of output power. At higher pump powers the laser generates 19 and 29 mW of mode-locked output power for pump powers of 200 and 300 mW, respectively.

Figure 3 shows a typical pulse duration and spectrum generated with a 200-mW pump. The pulse duration is 14 fs, and the corresponding spectrum is 91 nm. The transform limit of this spectrum yields a pulse duration of 10.4 fs, assuming flat spectral phase. The pulse duration was measured with an interferometric autocorrelator. The second harmonic was generated by focusing with a mirror into a 100-μm-thick KDP crystal. The excess group-delay dispersion from the output coupler and external optical elements was compensated for by external-cavity prisms, but correction for third-order dispersion is impossible with prism pairs. The interferometric autocorrelation yields a pulse duration of 14.0 fs, assuming a sech^2 pulse shape, corresponding to a time–bandwidth product of 0.554. The pulse duration exceeds the transform limit and is probably the result of excess third-order dispersion. The dispersion associated with air is higher than for standard 100-MHz repetition-rate lasers because of the longer cavity length associated with the 50-MHz repetition rate. This higher dispersion necessitates the use of prism separations that are longer than those of standard 100-MHz lasers and results in a higher third-order dispersion.

The KLM threshold is sensitive to the intracavity dispersion operating point, and the lowest pump threshold for starting Kerr-lens mode locking is achieved with the dispersion set to a more negative value than for optimum laser pulse duration. After mode locking is started, the dispersion operating point can be tuned toward zero to increase the bandwidth and achieve minimum pulse duration. When the intracavity prism insertion is set to optimize KLM start-up, output pulse durations of ~ 25 fs and bandwidths of ~ 40 nm are generated at 200-mW pump power. After Kerr-lens mode locking is started, the intracavity dispersion can be optimized to produce pulse durations of 14 fs and 91 nm. Output bandwidths of approximately 100 nm can be generated with

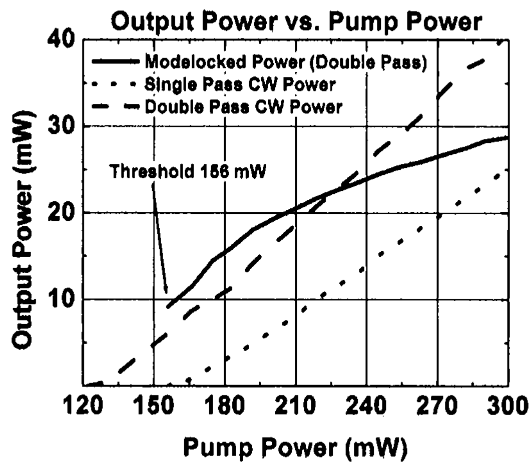

Fig. 2. Output versus pump power for mode-locked and cw operation. The use of a double-pass pump configuration, retroreflecting the unabsorbed pump light, increases the cw output power by approximately two times. Mode-locked operation is achieved with as little as 156 mW of pump power.

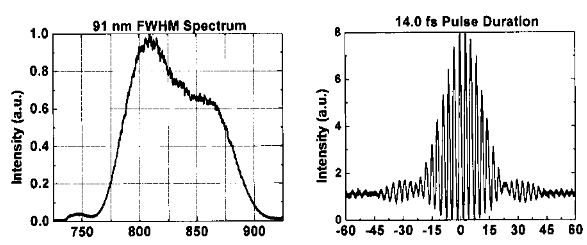

Fig. 3. Right, interferometric autocorrelation measurement of a 14.0-fs pulse (assuming a sech^2 fit) generated with 200 mW of pump power. Left, the corresponding output spectrum at 91 nm FWHM.

pulse durations of 14.7 fs when intracavity dispersion is tuned near zero. At higher pump powers the laser can be started at a dispersion operating point closer to where the optimum pulse durations and spectra are generated.

In conclusion, we have demonstrated ultralow-threshold operation of a mode-locked $Ti:Al_2O_3$ laser. Pulse durations as short as 14 fs and output bandwidths of as much as approximately 100 nm FWHM can be generated. The threshold for initiating and sustaining Kerr-lens mode locking is as low as 156 mW of pump power. With 200-mW pump power, the laser generates 19 mW of mode-locked output at 50 MHz pulse repetition rate. We believe that the laser design can be further simplified and performance significantly increased by use of double-chirped mirrors. The use of DCMs permits compensation for intracavity dispersion without the need for intracavity prism. Furthermore, DCM technology can compensate for third-order dispersion, enabling extremely broad bandwidths to be generated. Pulse durations of 7–8 fs have been generated with bandwidths of ~250 nm FWHM by third-order dispersion compensating DCMs and pumping at standard pump powers.[10] It should be possible to develop ultralow-threshold lasers by use of third-order compensating DCMs. Reducing the pump power requirements to a factor of 10 less than for conventional KLM lasers will enable high-performance, ultralow-threshold $Ti:Al_2O_3$ lasers to be built at a fraction of the cost of standard femtosecond $Ti:Al_2O_3$ lasers, which we hope will permit much wider use of femtosecond laser technology.

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