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The development of long-cavity lasers requires careful design, because the operation of KLM depends critically on laser-cavity design. The laser cavity must be operated in a particular subset of its stability region and to optimize mode-locking performance.

As an approach to developing long-cavity lasers, we explored the use of Herriott-style MPC. This device has been used for spectroscopy of gases where long optical propagation paths in a gas cell are required. The MPC is constructed with a pair of curved mirrors separated by a given distance. The mirrors have notches cut in them to introduce and extract the optical beam. The optical beam is introduced into the MPC so that it strikes the first mirror off center and subsequently bounces between the two mirrors in a circular pattern, where it can be extracted after a given number of passes. The beam is also focused on subsequent bounces so that its propagation resembles propagation through a periodic lens array. This device is designed so that it provides a unity transformation of the parameter of the laser beam after a given number of transits. Thus, if this device is inserted into the KLM cavity, it can be designed so that it has zero effective length and leaves the laser cavity mode and nonlinear focusing behavior invariant.

The laser consists of a standard, dispersion-compensated KLM Ti:Al$_2$O$_3$, with MPC incorporated into one of the arms (Fig. 1). Mode locking was achieved at 15 MHz repetition rate, where the MPC has two mirrors M1 and M2 separated by 82.4 cm and the beam made 20 round-trip passes between the mirrors (Fig. 2). At 3.5 W pump power, we obtained 140 mW average output power and 20-fs nearly transform-limited pulse duration centered at 807 nm (Fig. 3). This implies a peak power of $\approx 0.5$ MW. Furthermore, because the pulse repetition rates are significantly lower, parasitic effects in ultrafast measurements using this source will be significantly less than for conventional high-repetition-rate 100-MHz lasers.

One limitation to the available pulse energies in our system was imposed by multiple-pulse instabilities that tend to arise at high pulse energies. This is a consequence of the high peak intensities present in this laser and the saturation of the self-amplitude modulation effects produced in KLM. Achieving high pulse energies requires a detailed understanding of the KLM mechanism and cavity operation because, as the laser cavity length is increased, the intracavity pulse energies and intensities are also increased to higher levels than in standard lasers. We are currently optimizing the pulse duration and output power performance to avoid multiple pulsing and to stably obtain a several-MW pulse peak power. In future work, the design and operating point of the laser will be extended to <10 MHz repetition rate.

In conclusion, mode-locked operation at 15 MHz has been demonstrated using a novel and long-cavity laser with an MPC. We successfully obtained 0.5 MW peak power and 20 fs nearly transform-limited pulse from KLM Ti:Al$_2$O$_3$ laser. This unprecedented low repetition rate laser suggests new approaches for achieving MW-level peak powers from laser cavities.

We thank Igor Bilinsky for scientific assistance. We would like to thank CVI Incorporated for help in designing the mirrors used in this study.

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CThJ6 Fig. 2. Mode-locked laser pulse train of 15-MHz repetition rate or 68-nm pulse separation at 50 ns/div.

CThJ6 Fig. 3. Intensity autocorrelation trace (a) and associated spectrum of 20 fs duration (b) from a KLM Ti:Al$_2$O$_3$ laser pulse.

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Pulse compression below 5 fs at MHz repetition rate: current status, prospects, and applications

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The basic recipe to generate ultrashort pulses consists of four main ingredients: (1) generation of white-light continuum (WLC) with
sufficient spectral bandwidth, (ii) measurement of the spectral phase of the resulting WLC, (iii) design of a compressor suitable for phase correction over the whole continuum bandwidth, and (iv) determination of the compressed pulse duration and its phase. In our setup, the required ultrabroad bandwidth of WLC is produced on injection of ~15-fs, 35-nJ pulses from a Millennia-pumped cavity-dumped Tisapphire laser into a single-mode fused silica fiber. Due to self-phase-modulation (SPM) in the fiber, the exiting pulse has a spectrum stretching from 500 nm to ~1.1 μm. Combined action of SPM and dispersion leads to a nearly linear group delay (Fig. 1, dotted line) over most of the spectrum, while the intensity profile (solid line) and the phase (dashed line) of the compressed 4.5-fs pulse retrieved via SHG FROG. The real part of the electric field is shown in the inset.

The sub-5-fs pulses are used in nonlinear optical experiments to study ultrafast chemical reaction dynamics in solutions. The high repetition rate, simplicity, and large spectral bandwidth (>500 nm) make this light source ideal for spectroscopic applications in condensed phase.

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Having succeeded previously in compressing the white light pulse below 6 fs by using exclusively chirped mirrors with reflectivity >98% in the range 550-1080 nm, our current work is aimed at substantial improvement of their dispersive properties. The synthesis of such mirror structures is based on a novel computation technique particularly developed for chirped mirrors. A new and more robust numerical engine for mirror design permitted a significant reduction in computation time and flexibility is desired dispersion properties.

We also foresee utilization of programmable phase masks for compensation of residual phase distortion remaining after the pulse compressor. Additionally, by applying such pulse-shaping techniques, variably delayed replicas of the pulse needed in numerous nonlinear optical experiments could be generated without optical beam splitting and recombining in an interferometrically stable setup.

Our white-light-producing setup also offers great versatility meeting demands of different spectroscopic applications. By using a wavelength-selective element, the laser is converted into a continuously tunable source of longer pulses (20-30 fs) over the entire spectral bandwidth of white light.

The 4.5-fs pulse retrieved via SHG FROG was resolved by means of second-harmonic generation frequency-resolved optical gating (SHG FROG).2

Fig. 1. The measured group delay of the white-light continuum as derived from SHG FROG measurements (dots), the group delay (solid line), and throughput (dashed line) of the three-stage compressor.

Fig. 2. The intensity profile (solid line) and the phase (dashed line) of the compressed 4.5-fs pulse retrieved via SHG FROG. The real part of the electric field is shown in the inset.

CThJ7 Fig. 1. Scanning electron micrograph of a finished bottom-emitting VCSEL PIE array.