in a fiber amplifier are approximately two orders of magnitude higher compared to the previously reported case of mJ energies and > 100 ns long pulses from a Q-switched multimode fiber laser.[6] Note that 400 ps stretching does not constitute a limit and ~1 ns stretched pulse durations are achievable with standard ~10-cm-wide diffraction gratings. This indicates the straightforward possibility of further energy scaling with this fiber system. Also, the use of 1800 1/mm gratings will allow to significantly reduce stretcher and compressor sizes. Furthermore, the robust fundamental-mode excitation and propagation properties of 50-μm core fiber indicate that further core-size scaling is possible with potential for even higher pulse energies.

5. References

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CMA2 — 8:30 am

High efficiency, single-stage, 7kHz, high average power ultrafast laser system

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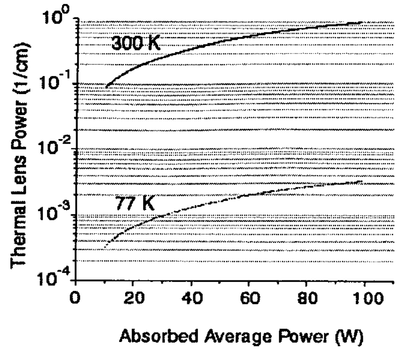
We demonstrate a single-stage, ultrafast Ti:sapphire laser amplifier system that operates at a repetition frequency from 1 to 10 kHz, with millijoule pulse energy, and up to 8 W average power. The repetition rate can be adjusted continuously from 1—10kHz, using new all-solid-state pump laser technology. This represents, to our knowledge, the highest average power ever obtained from a single-stage ultrafast laser amplifier system. This laser will significantly increase the average power and repetition rate easily accessible for high-field experiments such as coherent x-ray generation, or for laser-synchrotron studies.



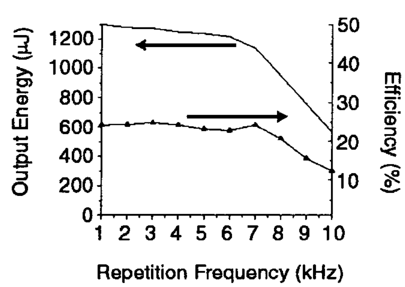
CMA2 **Fig. 1.** Thermal lens power as a function of absorbed pump power.

Ultrafast laser amplifier systems have been limited to relatively low energies (<100 μJ) for repetition rates above 5kHz[1] due to two factors. First, the available energy per pulse in a single pump laser at high repetition rates has not been adequate to date. Second, thermal lensing in the amplifier crystals becomes exceedingly strong[2,3] at high pump fluences, making the optical design both difficult and power dependent. In our work, we overcome these limitations by using a Corona (Coherent Inc.), diode-pumped, intracavity doubled, YAG laser system capable of delivering 90W at 10kHz. We also eliminate thermal lensing effects and significantly improve the beam quality and efficiency in the amplifier by using a liquid-nitrogen cooled cryostat to cool the Ti:sapphire below levels previously demonstrated.[3]

Thermal lensing is caused by the refractive index change of a crystal due to local heating when pumped at high average power. Two factors influence the thermal load: first the thermal conductivity determines how much heat can be removed from the pumped region; second, dn/dT determines how large the index change will be due to heating. Eqn. (1) shows the dependence of the thermal lens on these terms-

$$1/f = \kappa A/P_a(1/2\, dn/dT + \alpha C_{r,f}\, n_o^3 + \alpha r_o(n_o - 1)/L) \quad (1)$$

where κ is the thermal conductivity, A is the pumped area, P_a is the pump average power, dn/dT is the refractive index change with temperature, $\alpha C_{r,f}\, n_o^3$ is the elasto-optic term, and $\alpha r_o(n_o - 1)/L$ end face bowing term. The dominate parameters are κ and dn/dT. By cooling the amplifier crystal to 77 K, the thermal conductivity increases by factor of 10, while dn/dT decreases by 10. Under these conditions, we reduce the thermal lens effect by more than two orders of magnitude, as shown in Fig. 1. This approach completely eliminates drift and instability in the system due to minor pump variations, while also improving the beam quality and efficiency.



CMA2 **Fig. 2.** Compressed output energy and efficiency as a function of repetition rate.

The observed 24% efficiency is the highest ever reported at high average powers in a multipass amplifier. Figure 2 shows the laser performance, efficiency, and output energy. The highest average power of 13 W (1.86 mJ per pulse) is obtained at 7kHz, which gives 8 W compressed. The compressed pulse energy drops to 560μJ at 10 kHz due to a reduction in the available pump energy per pulse. We believe this to be the highest average power ever produced from a single stage ultrafast amplifier.

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CMA3 — 8:45 am

Femtosecond All-Solid-State Orange Laser

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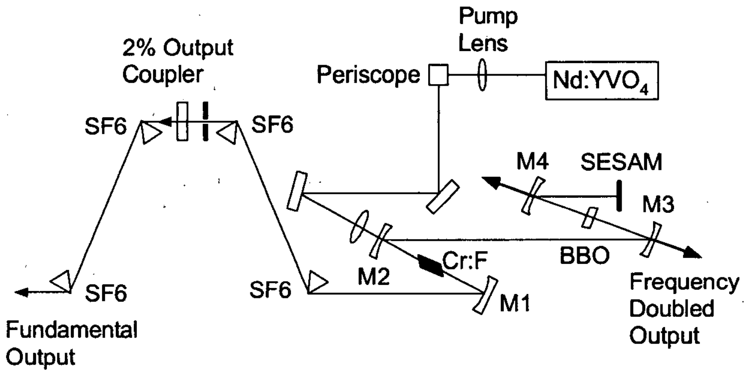
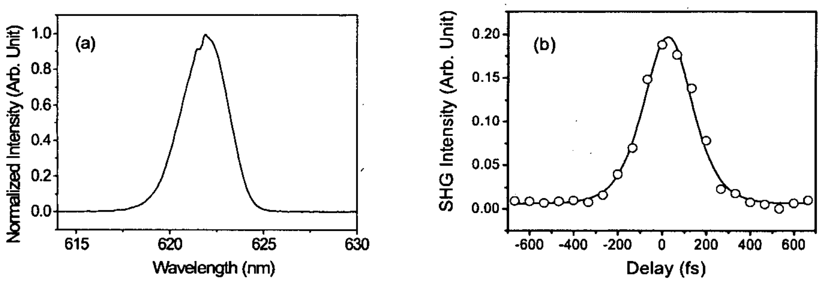
All-solid-state lasers shows advantages in compactness, stability, high output powers, and compatibility with newly developed mode locking mechanisms (like Kerr lens mode locking (KLM)). Even though the femtosecond solid state laser has already dominated the market for 10 years, there exists no femtosecond solid-state laser oscillator operating around 600–630 nm, which has already been widely applied for scientific studies during the dye-laser era. In this presentation, we demonstrate the first femtosecond mode-locked all-solid state laser oscillator covering the orange wavelength region of 600–630 nm. Femtosecond orange pulses with high average power was obtained directly from a laser oscillator by intracavity frequency doubling of a mode-locked Cr:forsterite laser using a BBO crystal. Intracavity frequency doubling shows advantages over external cavity frequency doubling[1–3] due to simplicity and efficiency considerations that are key points of using solid-state instead of dye lasers.[4]

Structure of the laser resonator is shown schematically in Figure 1. The laser was pumped with an 8W of 1064 nm light from a diode-pumped $Nd:YVO_4$ laser (Spectra-Physics Millennia IR). The modified Z-cavity consisted with a 2% output coupler, 4 laser mirrors (M1, M2, M3, M4), and a semiconductor saturable absorber mirror (SESAM). For intracavity frequency dou-



CMA3 Fig. 1. Schematic diagram for the intracavity frequency doubled femtosecond Cr:forsterite laser.



CMA3 Fig. 2. (a) output spectrum, (b) corresponding autocorrelation trace (open circles), and its sech square fit (solid line) of the intracavity frequency doubled femtosecond Cr:forsterite laser.

bling, the employment of the SESAM would initiate and stabilize the femtosecond pulse generation. The focal point between M3 and M4 was reserved for the nonlinear doubling crystal. An SF6 prism pair was inserted to provide intracavity group-velocity dispersion compensation. Outside the cavity, we use another SF6 prism pair to achieve both beam shaping and dispersion compensation of the fundamental output.

Without insertion of the BBO crystal, 110 mW stable fundamental output power can be obtained at 1230 nm with 215 fs FWHM, indicating 140 fs pulse width when a sech square profile was assumed. After placing a 1 mm-thick BBO crystal with type I phase-matching at the focal point between M3 and M4, stable generation of 24 mW frequency-doubled orange output could be obtained while the corresponding fundamental output power was dropped to 95 mW. The repetition rate was 81 MHz, which was synchronized with the fundamental pulse train. Figure 2(a) shows the measured spectrum of the frequency-doubled output with a bandwidth of 2.9 nm centered at 622 nm. Its corresponding autocorrelation trace (See Fig. 2(b)) shows 260 fs FWHM with a $sech^2$ intensity profile, indicating 168 fs pulse width. The time-bandwidth product is 0.378, which is 1.2 times the transform limit (0.315) of a $sech^2$ pulse. By tuning the phase-matching angle, the orange output spectrum was found to be tunable between 610–630 nm with a bandwidth around 3–4 nm.

In this presentation, we will also discuss the effect of surface coating and different SHG crystals. Higher average output powers can be obtained by using different doubling crystal with a different output coupler. The bandwidth performance of this orange modelocked laser was found to be strongly modified by the surface coating the doubling crystal at the fundamental wavelength.

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CMA4 **9:00 am**

Bulk Er:Yb:glass soliton femtosecond laser

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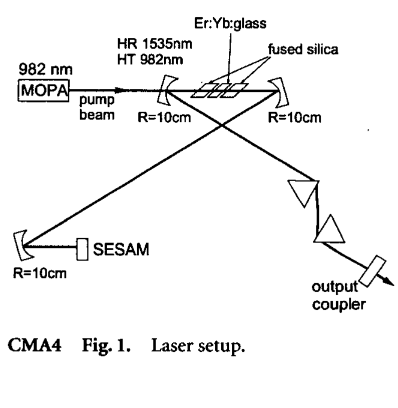
A bulk solid state Er:glass laser can combine the advantages of existing Er:fiber lasers, i.e. femtosecond pulses,[1] with pulse-width tunability and low phase noise. Moreover, the combination of low-cost glass and pumping by a relatively low-power diode laser is competitive to other bulk gain materials, e.g. Cr:YAG crystals using a pump power of several Watts, working at the eye-safe and telecommunications wavelength around 1.5 µm. However, the shortest pulses reported for a bulk Er:glass laser were limited to 2.5 ps.[2] To overcome the limitation to the picosecond regime we increased the intracavity self-phase modulation in order to achieve soliton mode-locking. This was realized by the insertion of an additional Kerr medium in the focal region of the resonator, fig. 1.

The pulses are initiated and stabilized by a relatively slow semiconductor saturable absorber mirror (SESAM in setup in fig. 1), however, strong self-phase modulation and low anomalous dispersion allow for soliton dynamics to form ultrashort pulses. Self-phase modulation originates from the nonlinearity of the resonator enhanced, as already mentioned, by sandwiching the Er:glass at the beam waist between two 9.5-mm fused silica glass plates which serve as an additional Kerr medium. The round-trip dispersion is adjusted by a pair of fused silica prisms.

Using an output coupler of 1.7% transmission yielded a cw output power of up to 92 mW at a total incident pump power of 600 mW. The shortest pulses obtained were produced with an average output power of 60 mW at the repetition rate of 100 MHz and were limited to τ = 600 fs (FWHM). To decrease the pulse length, we exchanged the output coupler to high reflector mirror ($T \approx 0.1\%$). The aim was to increase the intracavity intensity and to obtain in this way stronger self-phase modulation. As a result, the pulse length shortened to 380 fs (fig. 2) indicating that there is the potential for a further reduction of the pulse duration. The output power was then about 4 mW, transmitted however by each HR-mirror of the cavity, when pumped with 574 mW. Independent of the laser parameters, the pulses were Fourier-limited with the average time-bandwidth product of $\Delta\nu \cdot \tau = 0.320 \pm 0.013$.

We investigated the pulse shaping dynamics in dependence on pump power and intracavity dispersion. We compared the experimental results with the predictions of the soliton mode-locking model. According to the soliton model, the product of pulse length τ and the average output power P_{out} is proportional to the group velocity dispersion D, $P_{out} \cdot \tau \propto D$,[3] for a given nonlinear refraction index of the cavity. Fig. 3 shows the dependence of this product on the output power for three values of D, adjusted by



CMA4 Fig. 1. Laser setup.