High-power diode-pumped Yb^{3+}:CaF_2 femtosecond laser

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We report what is believed to be the first demonstration of a high-power passively mode-locked diode-pumped femtosecond laser based on an Yb^{3+}:CaF_2 single crystal, directly pumped by a 15-W fiber-coupled laser diode. With a 5-at.% Yb^{3+}-doped sample and prisms for dispersion compensation we obtained pulses as short as 150 fs, with 880 mW of average power and up to 1.4-W average output power, with a pulse duration of 220 fs, centered at 1049 nm. The laser wavelength could be tuned from 1040 to 1053 nm in the femtosecond regime. Using chirped mirrors for dispersion compensation, the oscillator provided up to 1.74 W of average power, with a pulse duration of 230 fs, corresponding to a pulse energy of 20 nJ and a peak power of 85 kW. © 2004 Optical Society of America

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In the past 10 years femtosecond laser sources have made possible decisive steps in numerous scientific and industrial fields, and they have become essential for a large range of applications such as nonlinear microscopy, ultrafast spectroscopy, micromachining, and optical coherent tomography.[1–3] The needs of the scientific and industrial worlds are continuously pushing the search for more compact, efficient, and relatively cheap lasers that will possibly provide high pulse energy and (or) high average power.[4] As a matter of fact, several groups worldwide are undertaking efforts by using different approaches.[5–9] Yb-doped materials are established to be particularly suitable for directly diode-pumped, high-power, solid-state sources.[10] This is due mainly to their weak thermal load and to their broad absorption band, which has a good match with the emission band of well-developed InGaAs diode lasers. Additional advantages are a simple electronic structure that avoids loss processes such as concentration quenching, upconversion, and excited-state absorption and a long upper-state lifetime (millisecond range). Yb-doped hosts have definitely been shown to be attractive for femtosecond oscillators[8,9] and amplifiers,[11] and they have recently reached a very high power level in the subpicosecond regime.[7] Generally these materials can be grouped into broadly tunable ones: glasses or crystals with low thermal conductivity, such as Yb^{3+}:$Sr_3Y(BO_3)_3$,[8] Yb^{3+}:$SrY_4(SiO_4)_3$,[9] or Yb:$KGd[WO_4]_2$,[12] used in femtosecond lasers, and crystals such as Yb:YAG (Ref. 7) that show higher thermal conductivity, supplying high output power but having narrower emission spectra. The new crystal Yb^{3+}:CaF_2, finally, contributes to bridging the gap between these two families and combines a very broad emission cross section (920–1100 nm) with a high undoped thermal conductivity of $\sim 9.7\ \mathrm{W\,m^{-1}\,K^{-1}}$, comparable with that found for YAG, and it exhibits advantages similar to those of $KGd[WO_4]_2$ (Ref. 12) and $KY[WO_4]_2$.[11]

CaF_2 is a well-known laser crystal: in fact, what are to our knowledge the first diode-pumped laser[13] and the first ceramic laser[14] were based on a CaF_2 matrix. Moreover, CaF_2 is relatively easy to grow in the form of large, good quality bulk crystals, and it has such a large transparency (0.15–9 μm) that it is used to build commercial optics from the ultraviolet to the infrared region. This material can be produced as large single crystals, but it is also potentially suitable as a ceramic laser host, because of its cubic structure. CaF_2, doped by divalent rare-earth ions such as Sm^{2+}, has been studied and used for many years.[15] Doped with trivalent rare-earth ions such as Er^{3+} and Tm^{3+}, CaF_2 recently yielded efficient and broadly tunable cw laser operation near 2.8 μm (Ref. 16) and 1.8 μm.[17] Doped with Yb^{3+}, CaF_2 recently turned out to be suitable for broadband[18] and high-power diode-pumped[19] laser operation near 1 μm.

The laser crystals used in this study were grown by use of the Bridgman technique and have broad and weakly structured absorption and emission bands (Fig. 1), principally because of their rich multisite

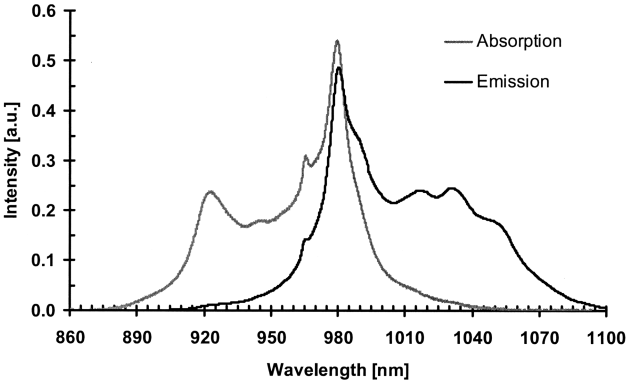

Fig. 1. Absorption and emission spectra of Yb^{3+}:CaF_2 crystal at room temperature.

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structure, which is due to the necessary change compensation that follows the Yb^{3+}/Ca^{2+}-ion substitutions. For femtosecond operation we chose a Brewster-cut, 4-mm-long, 5-at.-% Yb-doped CaF_2 crystal. The pump source was a fiber-coupled laser diode with a 200-μm fiber core diameter and a numerical aperture (NA) of 0.22 that emitted as much as 15 W of power near 979 nm at maximum power. The broad absorption band of our crystal relaxes the constraints on the diode temperature control and lets the absorbed power be nearly 70% of the incident power at any pump level, under nonlasing conditions. The setup of the femtosecond oscillator is shown in Fig. 2. The pump light is focused inside the active medium to a beam diameter of 200 μm, by using a couple of 60-mm focal-length doublets. The crystal is placed in contact with use of indium foils to a water-cooled copper mount, with the temperature set to 12 °C. The cavity is designed to sustain a fundamental mode with a beam waist of 75 μm × 85 μm in the crystal. To start passive mode locking we used a commercially available semiconductor saturable absorber mirror (SESAM; Batop, Germany) designed for a central wavelength of 1045 nm, with 1% saturable absorption and a saturation fluence of 30 mJ/cm^2. We selected a mirror with a 300-mm radius of curvature to focus the cavity mode to a waist of 100 μm × 130 μm on a semiconductor saturable absorption mirror. The astigmatism caused by the crystal and the off-axis mirrors was not compensated for. The dispersion resulting from CaF_2 crystal was calculated from Sellmeier's equations[20] to be $\sim 145\ fs^2$. The dispersion of the crystal and the self-phase modulation given by Kerr nonlinearity of the gain medium were compensated for by a pair of LAK31 prisms separated by 27 cm. In a preliminary test in the cw regime this oscillator provided 1.9 W at 1049 nm with a 10% output coupler (SESAM replaced with a high-reflectivity mirror).

With a 4.5% output coupler we achieved mode-locking operation with a pulse duration of 220 fs, centered at 1049 nm, and an average power of 1.4 W, with 15 W of incident power. The corresponding fluence on the SESAM was $E \approx 1700\ mJ/cm^2$. We also acted on the slit near the output coupler to shift the wavelength and reduce the pulse duration. In that case 150-fs pulses, centered at 1043 nm, have been achieved, with a decrease of the average output power to 880 mW. The corresponding spectrum and the autocorrelation figure are shown in Fig. 3. In both cases the time–bandwidth product amounted to 0.33, indicating a close to transform-limited $sech^2$ pulse shape of a soliton. The repetition rate was 85 MHz. We found the threshold for stable mode-locking operation at ~350 mW of output power. Usually the pulse train kept stable for hours. We tuned the oscillator wavelength acting on the slit, providing a tuning range, in the femtosecond mode-locking regime, as broad as 13 nm, from 1040 to 1053 nm, with pulse duration variable from 200 to 440 fs (Fig. 4). In Fig. 5 we report the pulse duration and the average power obtained at different central wavelengths.

The laser also generated similar results with 4% and with 6% output couplers. In comparison with previous cw results presented in Ref. 16, we noticed a considerable increase of the cavity losses, above all as a result of depolarization in the crystal and of prism insertion. We measured a loss for each prism of ~2%. The amount of intracavity losses can explain the fact

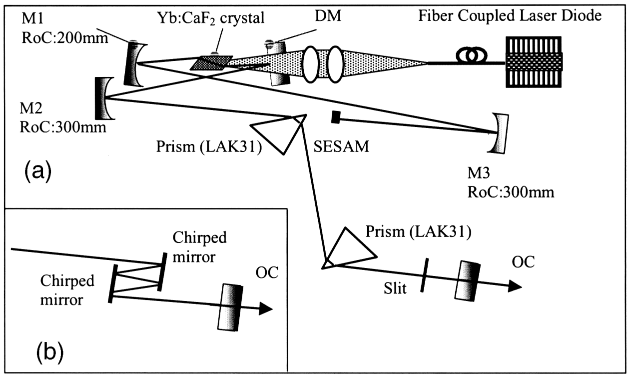

Fig. 2. Experimental setup for femtosecond oscillator. (a) Scheme with prisms: DM, plane dichroic mirror; RoC, radius of curvature; OC, output coupler. (b) Scheme with chirped mirrors in the case of four bounces on each mirror per round trip.

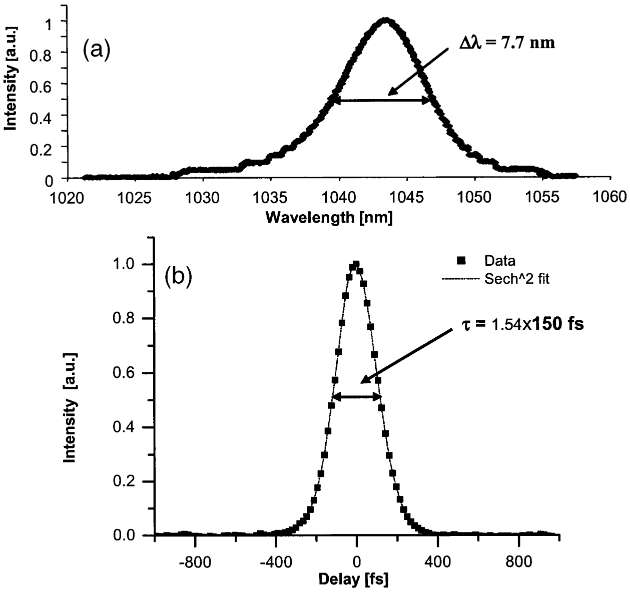

Fig. 3. (a) Spectrum of the mode-locked laser and (b) related figure of autocorrelation for the shortest pulse obtained.

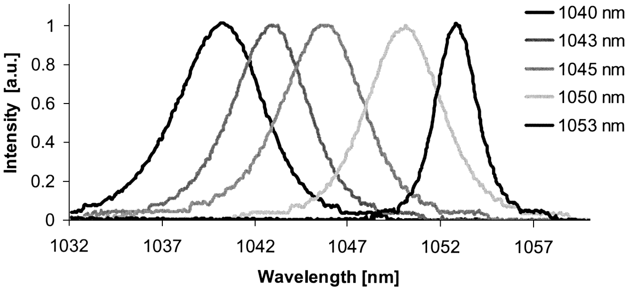

Fig. 4. Tuning curve of $Yb:CaF_2$ in the femtosecond regime, obtained with the cavity in Fig. 2(a), with dispersive prisms and the slit placed close to the output coupler.

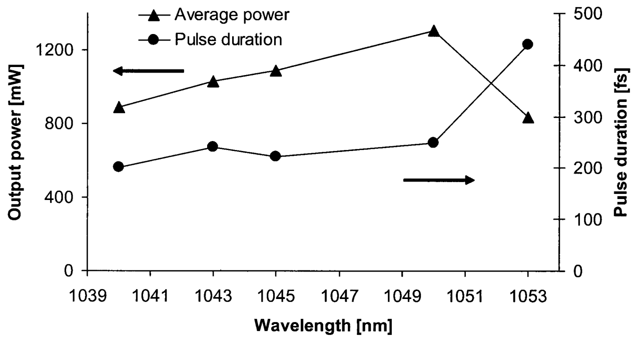

Fig. 5. Output average power and corresponding pulse duration as a function of wavelength.

that, in the 4–6% range of output coupling, we could not observe any fundamental changes in mode-locked behavior and results; the intracavity energy was almost constant in the different cases. With 10% and 15% output couplings we increased the cw output power, but we observed only Q-switched mode locking. We tried to improve our results in terms of pulse duration by changing the saturation losses of the absorber (2%), and the beam focusing onto the SESAM (with a mirror of 200-mm radius of curvature), but we observed damage on the saturable absorber surface and Q-switched mode-locking operation.

To reduce intracavity losses and to keep our oscillator more compact and robust, we performed a preliminary test with a pair of chirped mirrors (Layertec, Germany), each providing second-order dispersion compensation of nearly -550 ± 100 fs^2 in the spectral range from 1040 to 1090 nm. With two bounces on each mirror per round trip we achieved mode-locking operation, with a pulse as short as 230 fs at 1047 nm and average power of 1.74 W. Given the repetition rate of 88 MHz, this corresponds to a pulse energy of nearly 20 nJ and a peak power of 85 kW. With four bounces on each chirped mirror per round trip we observed longer pulses, with a pulse duration of 400 fs, an average power of 1.55 W, and a repetition rate of 84 MHz. In these configurations the output coupler transmission was 4.5%.

We have presented what is to our knowledge the first diode-pumped femtosecond laser based on Yb:CaF$_2$ crystal. With a 5-at.% Yb^{3+}-doped sample we obtained pulses as short as 150 fs, with 880-mW average power, centered at 1043 nm. In another regime we reached as much as 1.4 W of average output power, with a pulse duration of 220 fs, centered at 1049 nm. The laser wavelength could be tuned from 1040 to 1053 nm in the femtosecond regime, with a duration variable from 200 to 440 fs. Preliminary tests showed that the use of chirped mirrors is promising for upscaling the average power. We plan to reduce pulse duration by employing shorter crystals with slightly higher doping levels, brighter pump laser diodes, and more appropriate chirped mirrors for dispersion compensation.

We can definitely affirm that the combination of the good thermal conductivity and the large fluorescence bandwidth of CaF$_2$ has been demonstrated here to be extremely favorable for ultrafast applications. Moreover, good knowledge of crystalline properties and growing processes of CaF$_2$ could be crucial for eventual industrial development, as this crystal can be grown rather easily by use of standard techniques, with large size and an excellent optical quality. Thus in the near future Yb:CaF$_2$ could allow one of the most important technological breakthroughs in the development of Yb-doped materials for femtosecond diode-pumped laser applications.

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