Efficient diode-pumped Yb3+:Y2SiO5 and Yb3+:Lu2SiO5 high-power femtosecond laser operation

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We report the mode-locked operation of two new Yb-doped oxyorthosilicates, Y_2SiO_5 (YSO) and Lu_2SiO_5 (LSO), that are longitudinally diode pumped. Yb:YSO supplied pulses as short as 122 fs with 410 mW of output power at 1041 nm. More than 2.6 W of average output power, for pulse durations of 198 fs at 1044 nm and 260 fs at 1059 nm for Yb:YSO and Yb:LSO, respectively, were provided. These are, to our best knowledge, the highest values ever obtained and the most efficient mode-locked laser in such a classic fiber-coupled diode-pumping configuration.

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In the field of near-infrared lasers, it is now well known that Yb-doped crystals make efficient directly diode-pumped solid-state devices.[1] Indeed, the Yb ion's electronic structure has only two manifolds, $^2F_{7/2}$ and $^2F_{5/2}$, which ensure few quantum defects (<10%) and avoid parasitic effects such as cross relaxation and excited-state absorption. As Yb^{3+} has a much larger emission band than the other rare-earth laser ions, it naturally becomes one of the best candidates for high-power (>1 W) mode-locked lasers. Its main drawback is its quasi-three-level scheme, requiring high-brightness pumping and making it highly sensitive to the laser host.

Glass hosts hardly reach the watt level of average power, as they are intrinsically limited by their low thermal conductivity. But, in spite of their much better (≈10 times) thermal conductivity, the choice of crystal depends strongly on the desired pulse duration and (or) average power. For example, for the sub-100-fs level, $YbSr_3Y(BO_3)_3$, (Ref. 2, Yb:BOYS), $Yb:SrY_4(SiO_4)_3O$ (Yb:SYS), $Yb:YVO_4$,[4] $Yb:KY(WO_4)_2$ (Yb:KYW),[5] and $Yb:KGd(WO_4)_2$ (Yb:KGW),[6,7] seem the most appropriate; for sub 250-fs pulse duration, but with 1 W of power, only three crystals tested, namely $Yb:CaF_2$,[8] $Yb:KGd(WO_4)_2$ (Yb:KGW),[6] and Yb:SYS//YAG,[3] were shown to be relevant. The research on new candidates that provide more than 1 W of output power with relatively short pulses is still important, as they could be interesting for biomedical applications or efficient seeding of amplifiers.

In this Letter we present two new crystals, $Yb^{3+}:Y_2SiO_5$ (Yb:YSO) and $Yb^{3+}:Lu_2SiO_5$ (Yb:LSO) with interesting potential to be short-pulsed high-power lasers, partly based on their crystallographic quality and in particular on their good thermal conductivity.

Yb-doped YSO and Yb-doped LSO are two oxyorthosilicate biaxial monoclinic crystals with congruent melting at ~2000 °C. As these oxyorthosilicate crystals are commonly used—with cerium doping—for scintillator applications, the technique for growing them is well known and controlled. It has already been demonstrated that they can be grown by the Czochralski technique in large sizes and mass produced with excellent optical quality. The Yb-doped samples that we used were grown by the Czochralski technique and cut and polished at the LETI–CEA, the laboratory of the two authors named first. The YSO and LSO samples, respectively 5% and 8% doped, were 2 mm long, antireflection coated at 1 μm, and oriented with the Y axis along the direction of propagation [YSO, $n_x=1.772$, $n_z=1.791$ at 1.06 μm (Ref. 9)].

The undoped conductivity of YSO and LSO, respectively 4.4 and 5.3 $W\,m^{-1}\,K^{-1}$, is quite high compared with that of other Yb-doped crystals, notably due to the high melting point temperatures of YSO and LSO.[10] Thermal conductivity usually decreases with the doping level, depending on the difference in molar mass between Yb and the substituted ion. As Yb, Lu, and Y ions are similar, the thermal conductivity decreases only to 3.6 $W\,m^{-1}\,K^{-1}$ for 5%-doped YSO and stays equal to 5.3 $W\,m^{-1}\,K^{-1}$ for 8%-doped LSO. This ensures good heat removal and thermal management, the key characteristics for operating at high power pumping levels.

Both crystals offer relatively distorted occupation sites for Yb substitution, with coordinates 6(I) and 6 +1(II) statistically equally populated according to measurements of bulk Yb:YSO samples. The presence of two distinct occupation sites with low symmetry for the Yb^{3+} ion leads to a certain structural disorder, and hence, to fairly broad absorption and

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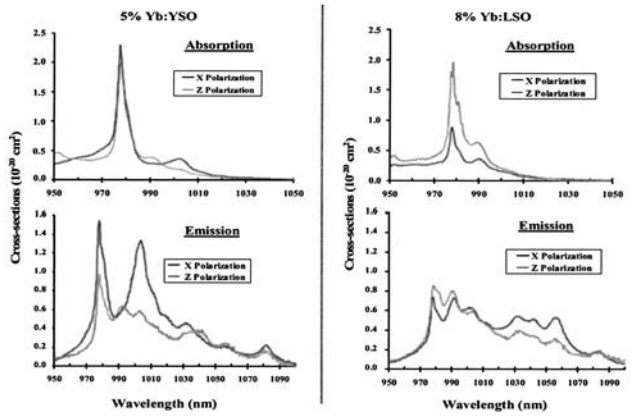

Fig. 1. Yb:YSO and Yb:LSO emission and absorption spectra for the X and Z axes as used for the experiments.

emission bands for Yb in these media. The emission spectrum indeed extends from 970 to 1100 nm, but reabsorption due to quasi-three-level emission prevents efficient lasing action below 1030 nm. The three main emission peaks are located near 1040, 1060, ($\sigma_e \approx 4 \times 10^{-21}$ cm^2), and 1080 nm ($\sigma_e \approx 2 \times 10^{-21}$ cm^2) (Fig. 1). The absorption spectra show a main peak close to 980 nm ($\sigma_a \approx 2 \times 10^{-20}$ cm^2), with residual absorption until 1030 nm. The broad respective absorption peaks permit good overlap with the 2.5 nm broad pump source (Fig. 1).

YSO and LSO also have strong internal fields owing to their structural disorder, which results in a large ground-state splitting [700 cm^{-1}(I);960 cm^{-1}(II)] compared with other Yb-doped crystals.[10] This helps to decrease the thermal population of the ground level and subsequently lowers the laser threshold and increases the lasing efficiency. Finally, the radiative lifetime of the $^2F_{7/2}$ manifold was measured to be 0.67 ms for Yb(5%):YSO and as long as 0.95 ms for Yb(8%):LSO.[11]

Preliminary cw experiments performed by Jacquemet *et al.*[12] have already shown promising results. With 14.4 W diode-laser pumping, output powers of 7.7 W at 1082 nm for the Yb:YSO crystal and 7.3 W at 1058 nm for the Yb:LSO crystal have been demonstrated; 60 nm broad tunability has been obtained with more than 4 W of average power.[12] This corresponds to an overall optical efficiency of more than 50%, which is better than that of Yb:CaF_2 and Yb:KGW crystals under the same conditions.

We performed femtosecond experiments in a standard Z-shaped cavity with two nearly collimated arms, one on each side of the crystal subcavity (Fig. 2). The pump source was a fiber-coupled laser diode delivering 15 W of power at 978 nm, with a 200 μm fiber-core diameter, reimaged into the crystal by a 60 mm doublet. We used a commercial semiconductor saturable absorber mirror (SESAM) from Batop GmbH to initiate the mode locking. This mirror was designed to operate near 1045 nm with a saturable absorption of 2%. With this device, stable mode-locked operation was observed near 1040 nm for Yb:YSO and in the 1060 nm region for Yb:LSO. The dispersion that was due to the YSO crystal had been estimated from Sellmeier's equations to be $\sim +400$ fs^2 on the X polarization and $+120$ fs^2 on the Z polarization per round trip. Nevertheless, to compensate for the positive dispersion, we used LAK31 prisms separated by 50–80 cm or two Gires–Tournois interferometer (G-TI) negative- dispersion mirrors (GTI mirrors from Layertec GmbH), providing -550 fs^2 per rebound. Both solutions provide negavitive dispersion near -2200 fs^2, which had proved experimentally to be the most fitting.

First we introduced the prisms into the experiments, which allowed us to investigate tuning in the mode-locked regime and usually to get the shortest pulses. The shortest pulses obtained for this configuration had a duration of 122 fs, with an average power of 410 mW with Yb:YSO (Fig. 3) and a 9.4 nm spectral bandwidth centered at 1041 nm. Time–bandwidth product $\Delta t \Delta \nu$ was 0.318, close to the transform-limited value (0.315), for all the mode-locked regimes observed. Unlike in the cw regime, the tuning range in the femtosecond regime with the Yb:YSO crystal turned out to be split into three regions (1034–1038, 1039–1043, and 1046 nm); the average power varied from 230 to 800 mW. Figure 4 represents such a tuning range for the three pulse-duration regimes. In this configuration for the Yb:LSO crystals, the shortest pulses had a duration of 257 fs with an average power of 430 mW, corresponding to a power spectrum bandwidth of 5.4 nm centered at 1059 nm. We could not find any noteworthy continuous tuning range for Yb:LSO: the crystal would switch stably from one mode-locked regime to another from 260 to 380 fs in a 300–430 mW range.

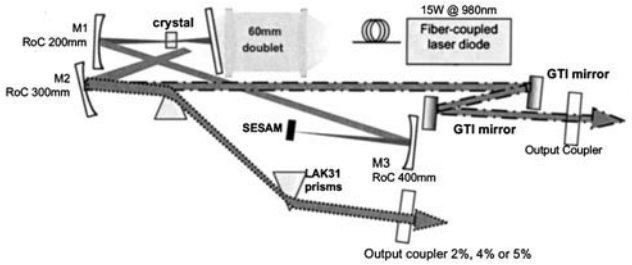

Fig. 2. Experimental setup for mode-locking experiments with LAK31 prisms or GTI mirrors inside the cavity. M1–M3, mirrors; RoCs, radii of curvature.

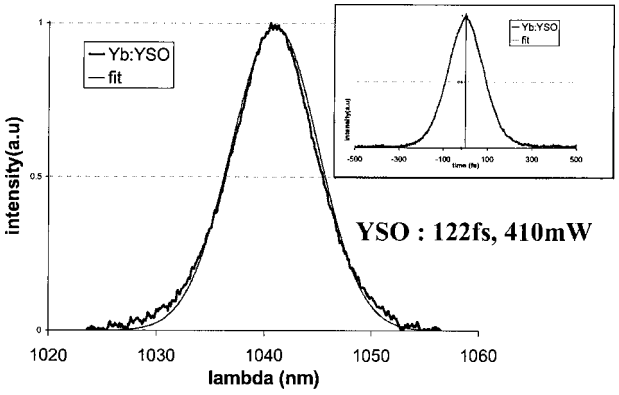

Fig. 3. Yb:YSO 122 fs, 400 mW configuration, the shortest pulses obtained with these crystals.

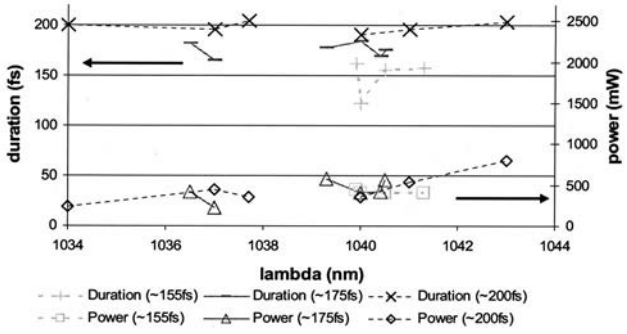

Fig. 4. Continuous femtosecond tuning ranges for Yb:YSO. The connected points represent domains where cw tunability in the femtosecond regime has been observed.

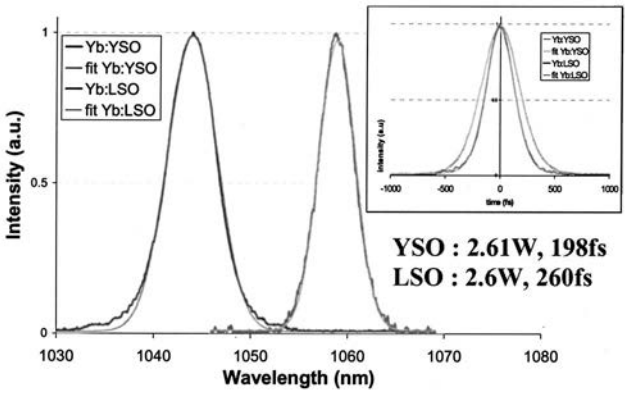

Fig. 5. 2.6 W average power operation with Yb:LSO and Yb:YSO crystals: autocorrelation traces and corresponding spectra.

This behavior is likely to be due to the spiky shape of the emission spectrum, contrary, for instance, to the smooth shape of Yb:CaF2, which exhibited 13 nm continuous tuning.[8]

We then used GTI mirrors to get high average power, as they introduced fewer losses than the prisms (Fig. 2). For the Yb:YSO crystal we got more than 2.61 W of average output power, with a pulse duration of 198 fs and a 5.8 nm bandwidth centered at 1044 nm (Fig. 5). Yb:LSO crystal also provided an average power of 2.6 W, with 260 fs pulses and 4.6 nm bandwidth centered at 1059 nm (Fig. 5). This corresponds to an overall optical-to-optical efficiency of 17% and a conversion efficiency above 25%, as the proportion of pump power absorbed in a single pass was measured to be 85% at maximum pump power. The laser operated at a repetition rate of 75 MHz, and the energy per pulse was then 35 nJ, leading to peak powers as high as 168 kW for Yb:YSO and 135 kW for Yb:LSO. We also obtained the shortest pulses for Yb:LSO within this configuration: 233 fs with 1.1 W of average power and a 5.2 nm bandwidth still centered at 1059 nm. All the mode-locked operations referred to here were stable for hours, with $\Delta t \Delta \nu$ near 0.32 and an excellent beam quality.

In conclusion, we have demonstrated, for the first time to our knowledge, mode-locked operation of two Yb-doped orthosilicates, Yb:YSO and Yb:LSO. They turned out to be efficient materials and provided 2.6 W of average output power with 198 and 260 fs pulse durations, respectively, leading to 17% overall optical efficiency, values that we believe are the highest obtained for this classical fiber-coupled diode-pumping configuration. Yb:YSO also produced 122 fs pulses with more than 400 mW of power when Yb:LSO decreased to 233 fs with more than 1.1 W of output power. Their tunability, in contrast, was limited. Finally, they are easily grown to large sizes under well-known and controlled conditions, as they have been industrially grown for years for scintillator applications. They could be promising materials for compact and cost effective femtosecond lasers in the multiwatt range.

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