Directly diode-pumped Yb3+:SrY4(SiO4)3O regenerative amplifier

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We report a regenerative amplifier based on an Yb-doped apatite crystal: $Yb^{3+}:SrY_4(SiO_4)_3O$ (Yb:SYS). We obtained 420-fs pulses at a central wavelength of 1066 nm with an energy of 100 μJ at 300 Hz after compression. To the best of our knowledge, this system is the first regenerative amplifier based on an Yb:SYS crystal and provides duration among the shortest ones generated by a directly diode-pumped regenerative amplifier.

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In the field of femtosecond lasers, Ti:sapphire lasers are unique with regard to their excellent spectral and thermal properties. However, directly diode-pumped solid-state lasers lead to more compact, cost-efficient, and reliable laser systems. Cr-doped and Nd-doped media are thus interesting but have major issues for the generation of high-energy ultrashort pulses because of respective thermal problems and relatively narrow emission bandwidths. With a simple electronic structure and a broad emission bandwidth, Yb-doped media seem more appropriate to develop such systems.[1] Besides, because of the commercial availability of high-power, high-brightness InGaAs laser diodes emitting around 980 nm (corresponding to the most intense absorption line of Yb-doped laser materials), Yb-doped media have been widely studied for the development of solid-state lasers, especially for ultrashort pulse generation. In particular, Yb:glass allows us to produce pulses as short as 200 fs with a chirped-pulse amplification system[2] but at a low repetition rate and with a complex system having low thermal conductivity and a low emission cross section of glass. Despite a narrower emission bandwidth, crystals such as Yb:KGW or KYW lead to interesting results[3,4] because of their high emission cross sections and relatively good thermal conductivity. To obtain shorter pulses without losing the relatively good gain and thermal properties of the crystals, some recently discovered Yb-doped crystals[5,6] appear to be potentially suitable for the purpose. These new crystals are a good compromise because of their broad emission bandwidths (greater than for Yb:KGW or KYW), their relatively high thermal conductivity (two to three times greater than for Yb:glass), and their relatively high emission cross sections (eight times greater than for Yb:glass).

Yb:apatite class crystals and especially fluoroapatites (such as Yb:SFAP) have good properties because of their intense emission cross-sectional peaks.[7] However the spectral bandwidths of these peaks are narrow, which makes them unusable for femtosecond pulse generation.[8] Here we report the results obtained with a new promising Yb-doped apatite crystal used in a regenerative amplifier, the $Yb^{3+}:SrY_4(SiO_4)_3O$ (also known as Yb:SYS), which belongs to the apatite-structure family but has a relatively high lattice structural disorder.[9] This silicate oxyapatite crystal has a broad emission band (Fig. 1) because of an equally random distribution of strontium and yttrium on the same Wyckoff site and because of the multisite occupancy of Yb^{3+} into two yttrium sites (with a 3:1 ratio).[9] The peak emission cross section drastically drops down compared with other apatite crystals with a value of only 0.44×10^{-20} cm^2 at 1040 nm (in comparison with 6.2×10^{-20} cm^2 at 1046 nm in a Yb:SFAP crystal). In contrast, the emission bandwidth increases in comparison with other apatite crystals and is approximately 73 nm. Compared with other broadband Yb-doped materials (such as Yb:glass, Yb:GdCOB, or Yb:BOYS), Yb:SYS crystal has a broader and more intense emission peak with a relatively high emission cross section to nearly 1100 nm. Moreover, Yb:SYS has quite a long lifetime ($\sim$1.1 ms) and a relatively high thermal conductivity ($\sim$2.2 W/m/K for the undoped matrix).

As shown in Fig. 2, the spatially reshaped pump beam with 4-W emission and a 1 μm $\times$ 100 μm laser diode at 975 nm is focused on a 5-mm-long,

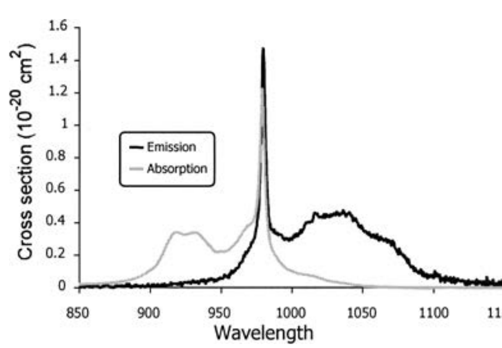

Fig. 1. Emission and absorption spectra of Yb:SYS.

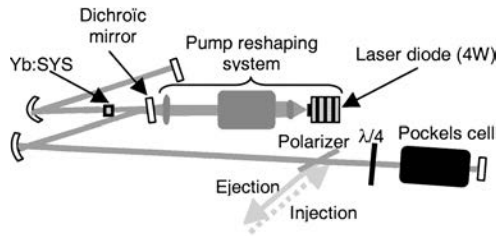

Fig. 2. Schematic diagram of the regenerative amplifier.

antireflection-coated, 6%-doped Yb:SYS crystal. The amplifier cavity was built to obtain, on the one hand, a collimated laser beam with a large spot size around the KD*P Pockels cell and, on the other hand, a cavity mode with a spot size of 270 μm in the crystal. The latter spot size allowed a relatively high gain and a fluence below the damage threshold. To be within the safe regime in terms of fluence level, we experimentally evaluated the damage threshold of the crystal coatings in the free-running and injected modes. Our results were higher than 0.2 and 0.3 J/cm^2. These values were obtained as a consequence of observed damage on the crystal coatings during experiments that were not dedicated to this purpose. Furthermore, these measurements took into account all the undesired effects such as relaxation peaks in the free-running mode. Considering the small gain available in this crystal, we had to find a compromise to extract the most energy in a minimum number of round trips without damaging the crystal. The cavity round trip was set to ~7 ns to fit with the high-voltage rise time of the Pockels cell. To control the injection of the femtosecond pulses, we added a thin-film polarizer and a zero-order quarter-wave plate into the cavity (Fig. 2).

Without injection, the Yb:SYS regenerative amplifier was Q switched with a pulse build-up time of 1.6 μs, which corresponds to approximately 240 round trips. At a 300-Hz repetition rate, the cavity-dumped Q-switched pulse contained 110 μJ of energy. The free-running pulse spectrum was centered at 1066 nm, with a spectral bandwidth of 2.7 nm. We performed a simulation of the Q-switched pulse buildup to evaluate the gain and the loss in the amplifier cavity. This simulation was based on a standard Frantz–Nodvik analysis that has been modified to take into account the quasi-three-level nature of the Yb^{3+}. According to this fit (Fig. 3), we obtained a single-pass small-signal gain of 1.10 and a single-pass loss of 5.1%.

The femtosecond mode-locked pulses (approximately 1 nJ of energy) of an Yb:SYS oscillator[10] were stretched to approximately 230 ps by an Offner triplet telescope stretcher[11] before being injected into the amplifier. The injected and amplified spectra are shown in Fig. 4. With an optimized injection, it took 840 ns (approximately 125 round trips) for the regenerative amplifier to extract 170 μJ of energy/pulse (before compression). Because of a high spectral gain narrowing (due to the high number of round trips), the FWHM of the amplified spectra was reduced to 3.4 nm for an injected pulse with a 10-nm FWHM spectra centered at 1066 nm. In other words, after compression, the amplified pulse duration would be at least 350 fs for Fourier-transform-limited pulses. After a grating pair compressor (transmission of 60%), we measured 420-fs pulses with 100 μJ of energy at a repetition rate of 300 Hz (Fig. 5). We estimate that this duration corresponds to the minimal duration limit of compression for 3.4-nm pulses. This experimental limit is due to the high stretching rate combined with the optical aberrations introduced by the stretcher. The corresponding time–bandwidth product was 0.38.

When we increased the repetition rate from 200 Hz to 3 kHz, the energy decreased from 100 to 65 μJ (energies measured after compression under less-optimized conditions than for our best result given in the preceding paragraph), whereas the pulse duration increased from 420 to 600 fs (Fig. 6). These results were due to the decrease of stored energy (Yb:SYS fluorescence lifetime is approximately 1 ms) and consequently to the increase of buildup time. One can observe that the energy can be increased at a high repetition rate by optimizing the spot size. But in this case, the spot size would be such that operating at a low repetition rate would induce damages.

In conclusion, we have demonstrated for the first time to our knowledge a directly diode-pumped regenerative amplifier that uses an Yb:SYS crystal. This

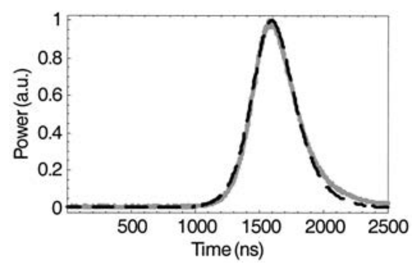

Fig. 3. Experimental intracavity Q-switched pulse (solid curve) and theoretical fit (dashed curve).

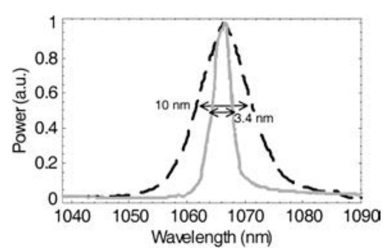

Fig. 4. Spectra of the pulses before (dashed curve) and after (solid curve) they were injected into the Yb:SYS regenerative amplifier.

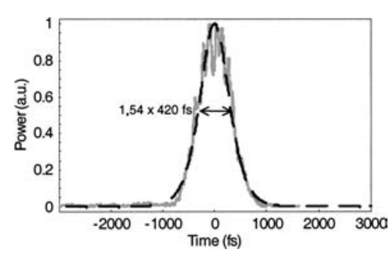

Fig. 5. Autocorrelation of the amplified pulses (solid curve) and sech^2 fit (dashed curve).

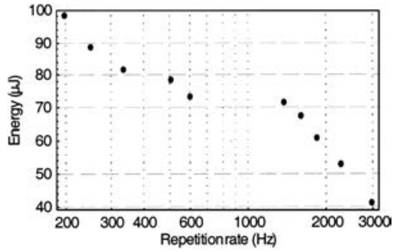

Fig. 6. Experimental output energy (after compression) versus repetition rate.

silicate apatite crystal has the unique property of undergoing a high structural disorder and thus shows a broad emission band. Yb:SYS seems to have potential because of its relatively high emission cross section (compared with other broadband Yb-doped materials) especially in the long-wavelength range (>1050 nm). We obtained 420-fs, 100-μJ pulses after compression with a buildup time of 840 ns and an amplified spectrum of 3.4-nm bandwidth centered at 1066 nm. Our regenerative amplifier shows interesting results compared with its main competitors: its output pulse duration is among the shortest and its global efficiency is greater than other Yb-doped regenerative amplifier efficiencies[2,12] (a duration range of between 200 and 500 fs). For now, by using a thinner Yb:SYS crystal to decrease reabsorption, we anticipate increasing the gain spectral bandwidth. If we compensate for the lower gain by decreasing the cavity spot size in the crystal, we can obtain the same pulse buildup time as before (with a lower extracted energy to stay under the damage threshold) but less spectrum gain narrowing. The output pulse energy (which is not our most important parameter) will be lower, but spectral bandwidth will be higher because of greater gain saturation, and so we can benefit from the broad emission bandwidth of this new crystal.

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