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Diode-pumped Yb:Sr$_3$Y(BO$_3$)$_3$ femtosecond laser

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We have developed a diode-pumped Yb^{3+}:Sr$_3$Y(BO$_3$)$_3$ (Yb:BOYS) laser generating 69-fs pulses, at a central wavelength of 1062 nm. This laser is mode locked by use of a semiconductor saturable-absorber mirror and emits 80 mW of average power at 113 MHz. This is, to our knowledge, the first mode-locked Yb:BOYS laser and the shortest duration obtained from an ytterbium laser with a crystalline host. The central wavelength can be tuned from 1051 to 1070 nm, for sub-100-fs pulses. We have also achieved an average power as high as 300 mW with pulse duration of 86 fs at 1068 nm.

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The Yb^{3+} ion has been recognized for a few years now as a very interesting dopant for materials involved in solid-state laser development and especially in the ultrafast-laser field. First, because of their very simple electronic-level scheme based on only two manifolds, and because they can be diode pumped, Yb-doped materials have made possible the development of very efficient, simple, and compact directly diode-pumped lasers.[1] Moreover, Yb-doped materials exhibit—with respect to their Nd-doped counterparts, for example—relatively broad emission spectra, which makes them very attractive for use in the realm of ultrafast technology.[2,3]

From the point of view of developing diode-pumped ultrashort-laser systems, it is crucial to look for Yb-doped materials with the broadest emission spectrum.[2,4–6] Among them, Yb glasses exhibit very large emission bandwidths and thus have made possible the production of 58-fs pulses,[2] but the poor thermal properties and very low emission cross sections (Table 1) of these glasses make it very constraining to use them because of subsequently induced low gain and very strong thermal effects. It is thus interesting to investigate Yb-doped crystals, which have a higher emission cross section and better thermal behavior (Table 1). The problem is that the crystalline structure also tends to keep the emission and absorption bands narrow (the emission bandwidth is only 10 nm wide for Yb:YAG, for example). The most appropriate material for ultrashort-pulse generation would therefore be a crystal with good spectroscopic and thermal properties but with spectral-emission broadness comparable to that of glasses.

In this Letter we report results obtained with a new crystal, Yb:Sr$_3$Y(BO$_3$)$_3$ (Yb:BOYS).[8] The rising interest in this crystal is due to its numerous advantages and its good qualities compared with those of its competitors, mainly its excellent spectral properties.[9] As shown in Fig. 1, the emission cross-section spectrum is actually quite broad, with a glasslike shape. Furthermore, the Yb:BOYS emission bandwidth is one of the broadest for an Yb-doped crystal and is even broader than those of several Yb-doped glasses, such as Yb:phosphate (Table 1). In addition, the Yb:BOYS crystal also has relatively high emission cross section and thermal conductivity, comparable to those of other borate crystals such as Yb:GdCOB. Another interesting property of Yb:BOYS is its broad absorption peak (6 nm) at the zero phonon line, almost twice as broad as those of other crystals. This characteristic is significant in the case of diode pumping, because it loosens the constraint on the spectral linewidth of the high-power diode, whose spectral broadness can be a limiting factor for diode-pumped systems.

The combination of these properties, which have already been corroborated by experiments in the cw regime in terms of large tunability and high efficiency,[10] makes the Yb:BOYS crystal the most suitable to date for the development of a very efficient ultrashort-pulse oscillator. In this Letter we report on our experiments in passive mode locking of an Yb:BOYS laser.

The experiment was performed with a 3-mm-long, antireflection-coated, 20%-doped Yb:BOYS crystal. The pumping system was composed of one or two 1 μm × 100 μm junction laser diodes emitting at 975 nm whose beams had been reshaped in the direction parallel to the diode-active area by use of a cylindrical afocal expander. Diode #1 emitted cw power of 1.6 W; its beam was collimated with a 15-mm objective, reshaped with an 8× cylindrical afocal expander, and focused with an 80-mm doublet.

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Table 1. Numerical Data on Typical Yb-Doped Materials Used in Femtosecond Oscillators

Characteristic Parameters	YAG	KYW[c]	KGW[d]	Glass	GdCOB[e]	BOYS
Emission spectral bandwidth (nm)[a]	10	24	25	35	44	60
Theoretical pulse duration (fs)	118	50	47	33	27	19
Emission cross section at the natural laser linewidth (10^{-20} cm^2)	2.2	3	2.8	0.05	0.35	0.2
Absorption bandwidth (nm)	3	3.5	3.5	7	3	6
Absorption bandwidth at the zero-line wavelength (nm)	968	981	981	975	976	975
Fluorescence lifetime (ms)	0.95	0.7	0.75	1.3	2.6	1.1
Thermal conductivity (W/m/K)	11	3.3	3.3	0.8	2.1	1.8
Experimental pulse duration (fs)	340	71[b]	112	58	89	69
Ref.	2	6	7	2	5	8, 9

[a] To take into account the large overlap between the emission and the absorption spectra, we measured the emission bandwidth by considering the FWHM gain cross-section broadness for a partially excited-state population ($\beta = 0.5$).

[b] We obtained this result by pure Kerr-lens mode locking.

[c] $KY(WO_4)_2$.

[d] $KGd(WO_4)_2$.

[e] $Ca_4GdO(BO_3)_3$.

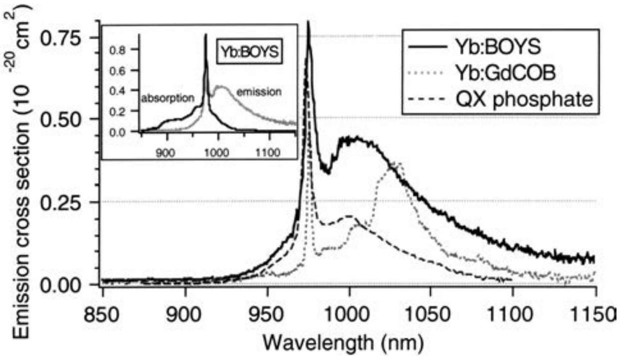

Fig. 1. Emission cross-section spectrum of Yb:BOYS compared with that of a typical Yb-doped glass, QX phosphate (Kigre, Inc.) and a borate crystal, Yb:GdCOB. Inset, emission and absorption cross spectra of $Yb:BO_5$.

Diode #2 emitted cw power of 2 W; its beam was collimated with an 8-mm aspherical lens, reshaped with a 4× cylindrical afocal expander, and focused with a 60-mm doublet. The incident pump power was 1.1 W with only diode #1 and 2.5 W with both diodes. The cavity setup is illustrated in Fig. 2; the laser spot size in the Yb:BOYS crystal had a waist of 27 μm. The group-velocity dispersion introduced by the crystal was compensated for by a pair of SF10 prisms separated by 28 cm. To initiate the mode-locking operation in the laser, we used a semiconductor saturable-absorber mirror (SESAM).[11] To optimize the pulse fluence on the SESAM, we used a 300-mm radius-of-curvature mirror to focus the cavity mode to a spot-size diameter of 80 μm on the SESAM for single-diode pumping and a 500-mm mirror with a spot-size diameter of 120 μm for two-diode pumping. The advantage of using a SESAM rather than Kerr-lens mode locking is that we avoid the need for critical alignment, leading to a more stable laser.[11] Moreover, the mode-locking instability is crucial, especially in the case of Yb-doped materials, which tend easily toward Q-switch regimes because of their long excited-state lifetimes.[12]

With this setup and when pumping with one (diode #1), we obtained pulses as short as 69 fs FWHM, assuming a sech^2 pulse shape (Fig. 3a). The corresponding spectrum (Fig. 3b) had an 18-nm FWHM bandwidth with a wavelength centered at 1062 nm, which corresponds to the natural free-running wavelength. The time–bandwidth product was 0.333 (to be compared with 0.315 in the Fourier-transform case for sech^2 pulses). The average output power was 80 mW for a repetition rate of 113 MHz, which corresponds to an energy per pulse of 0.7 nJ, or 10-kW peak power. The mode-lock operation was stable for hours, without evidence of dropping out or passive Q switching. The mode-locked regime was self-starting, with a transition time varying from 50 to 200 ms. The stable mode-locked regime was achieved with greater than 22 mW of average output power. The

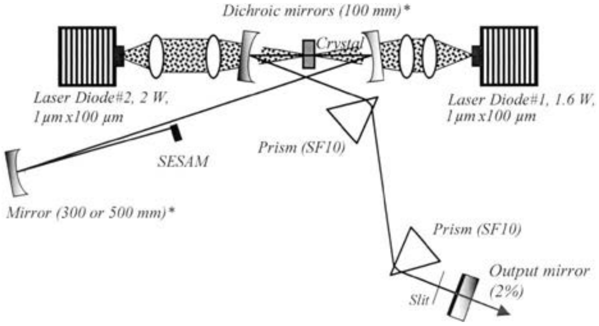

Fig. 2. Experimental setup of the femtosecond oscillator. Asterisks, values given for the radius of curvature.

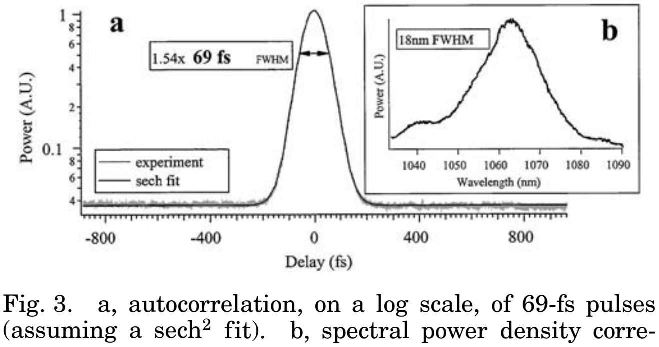

Fig. 3. a, autocorrelation, on a log scale, of 69-fs pulses (assuming a sech^2 fit). b, spectral power density corresponding to the same pulses.

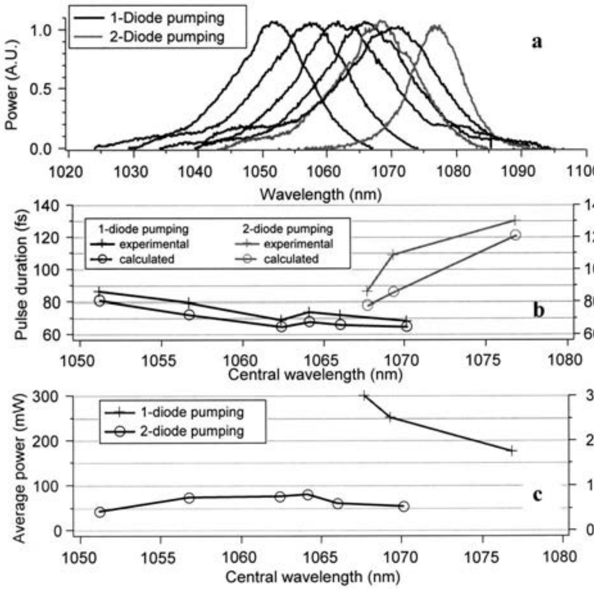

Fig. 4. Tunability of the Yb:BOYS femtosecond laser: a, pulse spectra; b, pulse duration measured experimentally with an autocorrelator and calculated by Fourier transform from the spectra, assuming no chirp in the phase; c, average power.

excellent stability of the mode-locked regime allowed straightforward tuning of the laser by translation of the slit located between the prism and the output coupler (Fig. 2). We thus obtained a range of tunability from 1051 to 1064 nm, with a pulse duration shorter than 86 fs (Figs. 4a and 4b), which is to our knowledge the largest tunability in this sub-100-fs range for an Yb-doped material. Moreover, by increasing the intracavity power (changing the output coupler), we extended this tunability continuously up to 1070 nm, with a tunability of 8 nm (and for sub-75-fs pulses), which then leads a total tunability of 19 nm.

To increase the power of the laser, we pumped the crystal from both sides. We obtained 86-fs pulses with an average power of 300 mW (Fig. 4c) at a repetition rate of 105 MHz. The spectrum was centered at 1068 nm (using the slit) and was 15 nm wide (Figs. 4a and 4b). In the two-diode-pumping configuration, the stable mode-locked domain allowed a tunability of 9 nm from 1068 to 1076 nm. The increase of the wavelength with two-diode pumping compared with single-diode pumping can be explained by the fact that, if we try to tune the laser to shorter wavelength, the mode-locked regime becomes unstable. In fact, when the central wavelength gets closer to the natural wavelength (1062 nm), the intracavity power rises to a level at which a cw regime tends to replace the mode-locked regime.

In conclusion, we have demonstrated what is believed to be the first Yb:BOYS mode-locked oscillator. This crystal gives very promising results, since it combines a broadband emission (glasslike) spectrum and the high laser efficiency of crystals,[10] and pulses as short as 69 fs have been obtained. Tunability for sub-86-fs pulses of 1051–1070 nm was also achieved. With higher-power diode pumping, 300-mW average power (33-kW peak power) was obtained for 86-fs pulses. Nevertheless, considering the broadness of the emission cross-section spectrum, we still have not taken advantage of full potential of Yb:BOYS. We are looking forward to improving our system for shorter-pulse generation by use of other more specifically designed SESAMs.

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