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Passive mode locking of a self-frequency-doubling $Yb{:}YAl_3(BO_3)_4$ laser

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We report passive mode-locking experiments with a novel self-doubling laser crystal $Yb{:}YAl_3(BO_3)_4$ (Yb:YAB). The diode-pumped laser was mode locked by an ion-implanted semiconductor saturable absorber mirror. Far off phase matching, soliton mode locking produced pulse widths of 198 fs to 1.4 ps, with up to 660-mW output and optical efficiency of 24% at 1040 nm. The shortest pulses had a peak power of 28 kW with 440-mW average power and 16% efficiency. A few degrees off phase matching, a total of 60 mW of green femtosecond pulses was generated simultaneously. Close to phase matching, the laser produced picosecond pulses and, without infrared output, a total of 270 mW of green output, corresponding to 10% conversion efficiency (absorbed pump to green output). © 2002 Optical Society of America

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Yb^{3+}-doped solid-state lasers have received much attention recently. Their simple energy-level scheme minimizes undesirable effects such as upconversion, excited-state absorption, and concentration quenching. Also, the small quantum defect (<0.1) and high quantum efficiency reduce the thermal load and associated problems. An important advantage of Yb^{3+}-doped laser crystals over their Nd^{3+}-doped counterparts is their broadband fluorescence, which allows tunability and (or) subpicosecond-pulse generation at wavelengths near 1040 nm. For instance, 340-fs pulses have been achieved in a semiconductor saturable absorber mirror (SESAM) mode-locked Yb:YAG laser with an average output power of $P_{\mathrm{av}} = 110$ mW.[1] In the thin-disk configuration the output of such a laser was scaled to $P_{\mathrm{av}} = 16$ W, albeit at the cost of longer pulse duration (730 fs).[2] Besides Yb:YAG, there is a growing range of SESAM mode-locked Yb^{3+}-doped lasers. Examples include the 40-mW, 90-fs pulses from a $Yb^{3+}{:}Ca_4GdO(BO_3)_3$ laser[3] as well as the 200-mW, 112-fs pulses from a $Yb^{3+}{:}KGd(WO_4)_2$ laser.[4]

Efforts to develop new crystal hosts for the Yb^{3+} ion have led to successful doping of $YAl_3(BO_3)_4$ (YAB).[5,6] Apart from its favorable laser properties,[7] Yb:YAB has a sizable second-order nonlinearity ($d_{\mathrm{eff}} > 1.4$ pm/V) and has so far been used in miniaturized cw and Q-switched lasers in the infrared and been highly efficiently self-doubled.[8] Note the recent extraction of 1.1 W of green output from a cw Yb:YAB laser with a pump-to-green efficiency of 10%.[9] Because of its fluorescence bandwidth of 20 nm (centered at 1040 nm), Yb:YAB is ideal for femtosecond-pulse generation in the infrared and the green.

In this Letter we report what is to our knowledge the first SESAM mode-locked, diode-pumped Yb:YAB laser. We achieved soliton mode locking by use of ion-implanted SESAMs. Far off phase matching, we obtained transform-limited pulses with pulse widths of 198 fs to 1.4 ps as well as average powers of 440–660 mW. A few degrees off phase matching, the infrared output was accompanied by as much as 60 mW of green femtosecond pulses. When the crystal was aligned close to phase matching, mode locking resulted in picosecond pulses in the infrared. Under these conditions, and without infrared output coupling, a total of 270 mW of green output was produced.

The cavity (see Fig. 1) contained a 2.5-mm-long, 5.6%-doped, antireflection-coated Yb:YAB crystal approximately at the focus between curved mirrors M_1 and M_2. We calculated $1/e^2$ mode radii of $w_x \approx 50$ μm and $w_y \approx 40$ μm inside the Yb:YAB crystal. During all experiments the crystal-mount temperature was held at 20 °C. Since the crystal was cut for second-harmonic generation with highest efficiency (type I phase matching), it was initially tilted by 20° (in the angle-tuning plane) to avoid efficient second-harmonic generation and strong phase modulation due to $\chi^{(2)}$ cascading near phase matching.[10] Propagating at an angle of ~12° to the phase-matching direction, the laser mode formed an

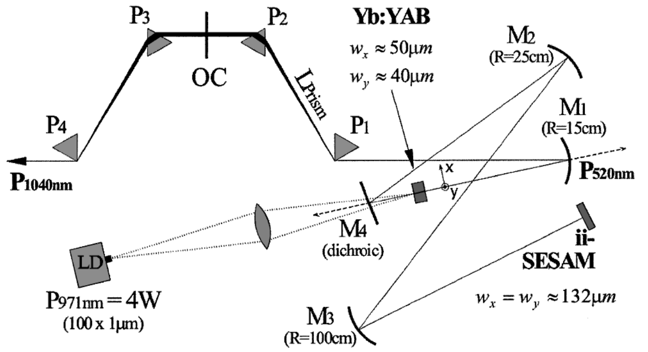

Fig. 1. Cavity layout of the SESAM mode-locked Yb:YAB laser. P_1–P_4, SF14 prisms; M_1–M_4, mirrors; OC, output coupler; ii, ion implanted.

o-ray (σ polarization) inside the negative uniaxial Yb:YAB crystal, resulting in the highest possible gain. Pumping was achieved with a 4-W, 100 μm × 1 μm aperture InGaAs laser diode (SDL-6380-A) with $\lambda_{\text{pump}} = 971$ nm and $\Delta\lambda = 3$ nm. The laser diode was imaged inside the crystal to a spot diameter of $d_x = 110$ μm × $d_y = 80$ μm and was delivered through a dichroic mirror (M_4). At the operational incidence angle of 10°, the reflectivity of M_4 for the laser mode was approximately 99.5%, and 85% of the pump was transmitted. The Yb:YAB crystal's broad ($\Delta\lambda_{\text{FWHM}} \approx 20$ nm) and strong ($\sigma_a = 3.4 \times 10^{-20}$ cm^2 at 976 nm)[6] absorption feature is ideal for diode pumping. Therefore, the crystal absorbed 2.7 W of pump power despite the nonideal pump wavelength.

Finally, net negative intracavity group-delay dispersion, which is required for soliton formation, was realized through a pair of minimum-deviation SF14 prisms. The group-delay dispersion was adjusted through insertion of prism P_2 and (or) variation of L_{prism} (see Fig. 1) without changing the overall cavity length ($f_{\text{rep}} = 70$ MHz). The spatially dispersed output was externally combined by prisms P_3 and P_4. It is well known that solid-state laser media with a long upper-state lifetime and a small emission cross section tend to Q switch or Q-switch mode lock in the presence of intracavity saturable absorption. With $\tau_u = 0.68$ ms and $\sigma_e = 0.8 \times 10^{-20}$ cm^2, Yb:YAB is comparable to other Yb^{3+}-doped lasers that operate on a quasi-three-level energy scheme and require high-brightness pumping. Furthermore, a picosecond SESAM response is critical for stable cw mode locking of these materials. We have developed an approach involving ion implantation and annealing of SESAMs grown at normal temperature with metal organic chemical-vapor deposition.[11] Compared with low-temperature molecular beam epitaxy,[12] this process is versatile, allowing for response time tailoring on the single-device level by variation of ion dose and annealing temperature. The resulting devices have excellent surface morphology as well as low nonbleachable losses and saturation fluences.

In the Yb:YAB laser we used different SESAMs, designed to give varying degrees of modulation. A half-wave layer of GaAs, grown upon a semiconductor Bragg mirror ($\lambda_B = 1040$ nm), contained as many as three 9.5-nm $In_{0.26}Ga_{0.74}As$ quantum wells at the antinode of the standing-wave power distribution. To generate a picosecond response, we implanted the SESAMs with 40-keV oxygen ions at a dose of 2×10^{14} cm^{-2}. All devices were then annealed at 600 °C for 20 min under arsine ambient. The saturation fluences of the devices were 20–30 μJ cm^{-2}, and their modulation was 0.5–1.5%, depending on the number of quantum wells and the mounting temperature.

Figure 2(a) and 2(b) depict the intensity autocorrelation and the infrared spectrum, respectively, of the shortest pulses from the laser, achieved with the highest-modulation SESAM, $L_{\text{prism}} = 350$ mm and $R_{\text{OC}} = 98\%$. Assuming sech^2 pulses, we deduce a pulse width of 198 fs and $\Delta\nu\tau_{\text{FWHM}} = 0.315$ from $\Delta\lambda_{\text{ir}} = 5.75$ nm. With $P_{\text{out}} = 440$ mW in TEM$_{00}$, we calculate a fluence on the SESAM of <600 μJ cm^{-2}, a peak output power of 28 kW, and an optical efficiency of 16%. Using higher output coupling ($R_{\text{OC}} = 94\%$), a SESAM with smaller modulation to prevent Q-switching instabilities, and L_{prism} as great as 540 mm, we achieved soliton mode locking of infrared pulses as long as 1.4 ps with $P_{\text{out}} = 660$ mW and 24% optical efficiency.

When we aligned the Yb:YAB crystal to within a few degrees off phase matching, P_{out} dropped to 380 mW with $\tau_{\text{FWHM}} = 245$ fs and some excess bandwidth ($\Delta\nu\tau_{\text{FWHM}} = 0.34$). Simultaneously, 22 mW of 520-nm radiation was measured extracavity at M_1. Because of the nonideal coatings for this wavelength on both M_1 and the laser crystal ($T < 85\%$), we infer that the total generated (bidirectional) power at 520 nm was greater than 60 mW. Figure 2(c) shows the spectrum of the green pulses under these conditions. This spectrum is in reasonable agreement with that expected from a calculation of Yb:YAB's phase-matching bandwidth of 0.46 nm cm. Although we could not measure the autocorrelation of the green pulses, their bandwidth of $\Delta\lambda = 1.2$ nm and the almost-transform-limited fundamental pulses suggest a pulse width of ~250 fs.

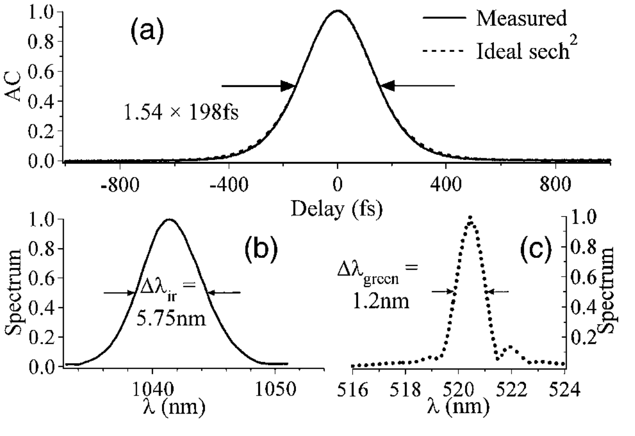

Fig. 2. (a) Autocorrelation (AC) of the shortest pulses (far off phase matching) together with that of an ideal sech^2 pulse. (b) Corresponding infrared spectrum. From $\Delta\lambda_{\text{ir}} = 5.75$ nm and $\tau_{\text{FWHM}} = 198$ fs we calculate $\Delta\nu\tau_{\text{FWHM}} = 0.315$. (c) Spectrum of green pulses (a few degrees off phase matching).

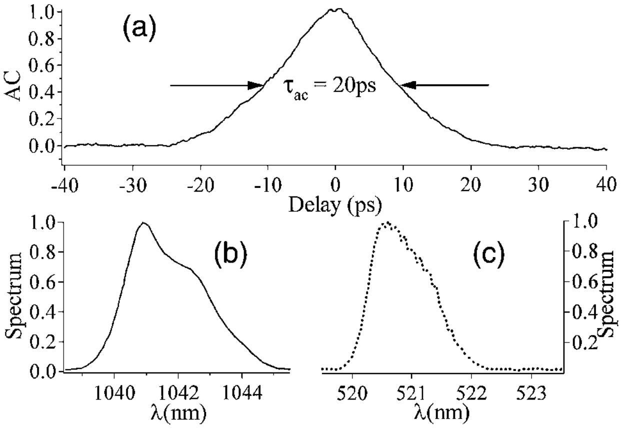

Fig. 3. (a) Autocorrelation (AC) of the infrared pulses (on phase matching). (b), (c) Corresponding infrared and green spectra, respectively.

To optimize the green output power, we replaced the output coupler with a high reflector and aligned the Yb:YAB crystal close to phase matching to maximize the output from M_1 (stable mode locking was not possible at phase matching, since the nonlinear loss to the pulse per round trip exceeded the modulation depth of the SESAM). Under these conditions the laser was still cw mode locked, producing picosecond pulses, although not in the soliton regime. Figures 3(a), 3(b), and 3(c) show the autocorrelation of the infrared pulses leaked through the high reflector and the fundamental and second-harmonic spectra, respectively. The combination of autocorrelation and spectra is reminiscent of chirped pulses, attesting to the strong influence on pulse formation of the second-harmonic generation and cascaded $\chi^{(2)}$ processes in this regime.[10] A maximum of 97 mW of green output was measured at M_1 when the cavity was operating with the highest-modulation SESAM. Obviously, the green output from this laser could be optimized by attention to issues such as coating designs. Using the same argument as above, however, we calculate the total amount of green power generated in the Yb:YAB crystal to be $P_{520\,\mathrm{nm}} > 270$ mW, corresponding to an absorbed pump-to-green efficiency of 10%. Consistent with earlier observations in a SESAM mode-locked Nd:LaSc$_3$(BO$_3$)$_4$ laser with a separate intracavity doubling crystal,[13] we observed as much as 10% rms noise on the pulse train for high conversion efficiency.

In conclusion, we have demonstrated passive mode locking of a self-doubling Yb:YAB laser. The diode-pumped laser was soliton mode locked by an ion-implanted SESAM. Far from phase matching, the laser produced transform-limited infrared pulses with pulse widths of 198 fs to 1.4 ps, average output power of 440–660 mW, and optical efficiencies of 16%–24%. The peak power of the shortest pulses was 28 kW. A few degrees off phase matching, the laser produced 245-fs pulses with some excess bandwidth ($\Delta\nu_{\mathrm{FWHM}} = 0.34$), together with a total of 60 mW of green femtosecond pulses. When the Yb:YAB crystal was aligned close to phase matching and the output coupler was replaced with a high-reflector, a total of 270 mW of 520-nm picosecond pulses was generated with an absorbed pump-to-green efficiency of 10%.

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