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Generation of 90-fs pulses from a mode-locked diode-pumped $\text{Yb}^{3+}:\text{Ca}_4\text{GdO}(\text{BO}_3)_3$ laser

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A diode-pumped $\text{Yb}^{3+}:\text{Ca}_4\text{GdO}(\text{BO}_3)_3$ (Yb:GdCOB) laser generating 90-fs pulses at a center wavelength of 1045 nm is demonstrated. This is, to our knowledge, the shortest pulse duration obtained from an ytterbium laser with a crystalline host. This laser is mode locked with a high-finesse semiconductor saturable-absorber mirror and emits 40 mW of average power at a repetition rate of 100 MHz. © 2000 Optical Society of America
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During the past few years the ytterbium ion has been recognized as an interesting dopant for efficient diode-pumped lasers.¹ Owing to its simple electronic structure² based on two electronic manifolds, the Yb ion has advantageous laser properties. First, the low quantum defect of this ion reduces the thermal load and thus thermal problems. Second, the absence of additional parasitic levels in Yb^{3+} eliminates undesired effects such as upconversion, excited-state absorption, and concentration quenching. Consequently, Yb provides the possibility of a high doping rate. Moreover, the absorption band in Yb-doped media (ranging from 900 to 980 nm) is covered by high-power InGaAs laser diodes that permit direct diode pumping and the development of efficient and compact all-solid-state lasers.

Yb-doped materials also generally exhibit broad emission bands compared with neodymium-doped crystals, for example, which are necessary for ultrafast lasers. With respect to short-pulse operation, it is interesting to compare two classes of Yb-doped solid-state laser materials: doped glasses and crystals. Until now, exclusively Yb^{3+} -doped glass lasers have produced pulse widths below 100 fs; e.g., 60-fs pulses were achieved for different kinds of Yb-doped glass matrices.^{3,4} The shortest pulse duration reported for an Yb-doped laser based on a crystalline matrix was 340 fs with Yb:YAG.³ The reason for this considerable difference in the minimum achievable pulse duration is the smoother and broader gain spectrum of the glasses. However, Yb-doped glass materials suffer from poorer thermal properties and smaller emission cross sections compared with crystals. For example, in the case of Yb:phosphate glasses the emission cross section is $0.05 \times 10^{-20} \text{ cm}^2$ (at 1060 nm) with a bandwidth of 62 nm, compared with an emission cross section of $2 \times 10^{-20} \text{ cm}^2$ and a bandwidth

of 12 nm for Yb:YAG. This large bandwidth leads to serious heat-load problems for high-average-power operation and significantly lowers small-signal gain and laser efficiency. Slope efficiencies of 80% were obtained with Yb:YAG in cw operation,⁵ in contrast to 49% for an Yb:phosphate glass laser.⁶ In addition, the small emission cross sections of Yb-doped glasses require more careful design of the laser parameters in passively mode-locked operation to suppress *Q*-switching instabilities in the mode-locked pulse train.⁷ Owing to this trade-off between solid-state lasers based on Yb-doped glasses and crystalline matrices, it would be useful to find a laser material with the capability to bridge the gap in terms of pulse duration, on the one hand, and emission cross sections on the other hand. We report in this Letter our experiments on passive mode locking of an $\text{Yb}:\text{Ca}_4\text{GdO}(\text{BO}_3)_3$ (Yb:GdCOB) laser. We first describe some favorable properties of the Yb:GdCOB crystal and subsequently present the results obtained with this crystal in the femtosecond regime.

The rising interest in the recently discovered Yb:GdCOB crystal can be explained by its numerous advantages.⁸⁻¹⁰ First, this crystal combines an emission cross section of $0.36 \times 10^{-20} \text{ cm}^2$ and a broad fluorescence spectrum of 44 nm. Second, Yb:GdCOB can be diode pumped at its zero-phonon line wavelength of 976 nm, leading to a quantum defect of only 7%. This small quantum defect permits high optical-optical conversion efficiency and reduces thermal problems. Furthermore, a large splitting of $^2F_{7/2}$ Stark levels in Yb:GdCOB,¹⁰ 1003 cm^{-1} compared with 628 cm^{-1} in Yb:YAG, makes the population of the transition lower level much less sensitive to temperature. Finally, the Yb^{3+} type of site in the oxoborate structure⁹ and the absence of concentration quenching

permit a high doping rate (as much as 27%) in Yb^{3+} in the GdCOB matrix. All these advantages have been corroborated by experimental results in the cw regime. At room temperature, with an absorbed pump power of 1.3 W, 814 mW of average power at 1040 nm with a slope efficiency of 77% has been obtained.⁸ Here we expand the previous cw results to show that Yb:GdCOB is also well suited for generation of ultrashort pulses.

The experiment was performed with a 3-mm-long, 15%-doped, antireflection-coated Yb:GdCOB crystal cut along its crystallophysic axis. The pumping system was a 2-W, $1 \times 100\text{-}\mu\text{m}^2$ junction laser diode emitting at 976 nm. The pump beam was collimated with a 4.5-mm lens, then reshaped in the slow direction with a $10\times$ cylindrical telescope, and finally focused in the crystal with a 30-mm lens. In this configuration the measured pump beam waist was $20\text{ }\mu\text{m} \times 70\text{ }\mu\text{m}$. The crystal absorbed only 580 mW of pump power because of the broad emission of the diode ($\sim 6\text{ nm}$) compared with the absorption band of the Yb:GdCOB crystal (2.3 nm). The laser cavity design is shown in Fig. 1. To produce short pulses we used a low-finesse semiconductor saturable-absorber mirror^{11,12} (SESAM) together with soliton-shaping processes. The absorber consisted of a double quantum-well structure that resulted in a modulation depth of $\sim 0.7\%$. The parameters of the cavity were optimized to avoid the Q-switched mode-locking regime, which is an important issue for Yb-doped lasers whose gain is relatively low.⁷ The beam waists were set near $45\text{ }\mu\text{m}$ on the SESAM and $70\text{ }\mu\text{m}$ in the crystal. A pair of SF10 prisms separated by 30 cm compensated for the positive dispersion inside the cavity and balanced the self-phase modulation introduced by the Kerr nonlinearity of the laser crystal to form solitonlike pulses. In this cavity a cw mode-locking regime was obtained with a stable pulse train at a 100-MHz repetition rate. The average output powers were 40 and 60 mW with, respectively, 1% and 2% transmission output couplers. The relatively poor efficiency of this laser compared with the cw results⁸ is due mainly to two factors. First, the large bandwidth of the pump poorly overlaps the absorption spectrum. Second, the prisms that we used exhibited large losses. The pulse duration was measured with a background-free second-order autocorrelator. Figure 2 shows the autocorrelation trace obtained with a 1% output coupler and corresponds to the shortest pulse obtained. The pulse duration is 90-fs (FWHM), assuming a sech^2 temporal intensity profile. The corresponding pulse spectrum, shown in Fig. 3, exhibits a FWHM bandwidth of 14.7 nm near 1045 nm, which yields a time-bandwidth product ($\Delta t \Delta \nu$) of 0.36 that is close to the Fourier-transform limit of 0.32. Using a 2% output coupler, we obtained 60 mW of average output power at a slightly longer pulse duration of $\sim 100\text{ fs}$.

We demonstrated the generation of green light in the femtosecond regime by using a second Yb:GdCOB crystal cut for second-harmonic generation. This crystal was cut for phase matching at 1020 nm; therefore the conversion efficiency at our operating center wavelength (1045 nm) was much lower than could potentially be achieved. No effect on the mode-locking

dynamics was observed in this low-conversion efficiency case. The GdCOB matrix has the possibility of exhibiting high-second order nonlinearity to permit self-frequency doubling.¹³ Despite the nonoptimal phase-matching angle of the crystal used, the intracavity peak power (approximately 130 kW) was sufficient to produce a few hundred microwatts of green light. Because of the spectral thickness, the spectral acceptance of this crystal is $\sim 2\text{ nm}$. The measured green spectrum (Fig. 4) had a bandwidth of only 2 nm, narrower than expected from the broadband fundamental spectrum. The spectrum calculated for these non-phase-matched conditions is plotted in Fig. 4 and

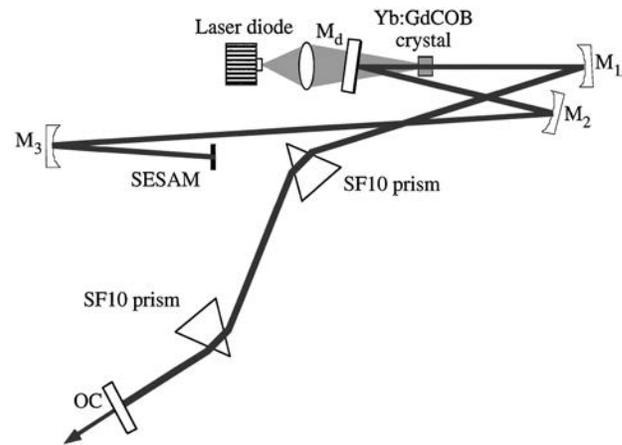


Fig. 1. Experimental setup: M_d , dichroic mirror with high-reflection coating for $\lambda > 1.01\text{ }\mu\text{m}$ and high-transmission coating for $\lambda < 0.990\text{ }\mu\text{m}$; M_1 , M_2 , M_3 , high-reflection mirrors with, respectively, 30-, 20-, and 15-mm radii of curvature; OC, 1% or 2% transmission plane output coupler; high-finesse SESAM.

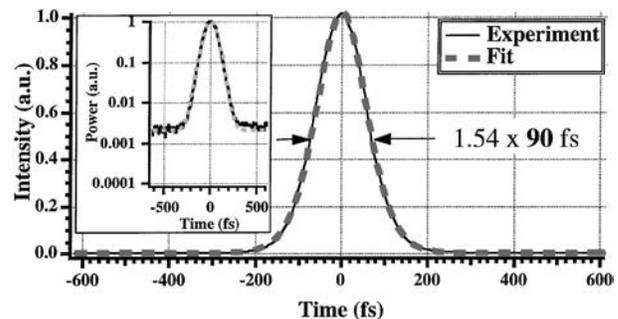


Fig. 2. Intensity second-order autocorrelation trace (solid curve) of the 90-fs pulses and its fit for a sech^2 intensity profile. Inset, the same graph on a logarithmic scale.

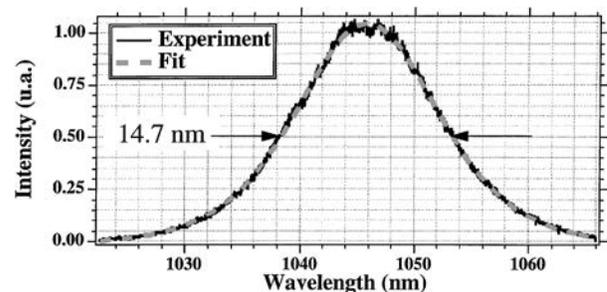


Fig. 3. Spectra of infrared 90-fs pulses.

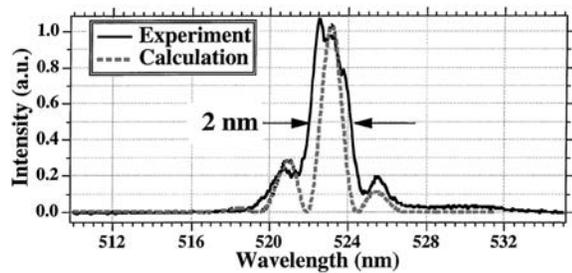


Fig. 4. Theoretical and experimental spectra of the green pulses.

shows good agreement with the experimental results. The production of short green pulses could be of interest, but we emphasize that intracavity self-doubling might not be the best solution for developing femtosecond lasers because Yb ion concentration requires a long crystal for efficient pump absorption, which leads to a narrow acceptance bandwidth for second-harmonic generation. Furthermore, efficient second-harmonic generation will almost certainly perturb the mode-locking process and be detrimental to stable operation.

In conclusion, we have demonstrated the generation of 90-fs pulses at 1045 nm with a diode-pumped Yb:GdCOB laser. With a corresponding spectral bandwidth of 14.7 nm, the solitonlike pulses were nearly Fourier-transform limited. Owing to its broadband fluorescence spectrum, Yb:GdCOB has produced the shortest pulse of which we are aware from an Yb-doped crystalline host. The properties of Yb:GdCOB make it interesting for the development of a new generation of efficient, compact, diode-pumped ultrafast chains (oscillator and amplifier). In fact, this crystal exhibits a much higher gain than Yb³⁺-doped glasses. The next development will be the application of Yb:GdCOB to a femtosecond laser amplifier.

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