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Diode-pumped continuous-wave and femtosecond laser operations of a heterocomposite crystal $Yb^{3+}:SrY_4(SiO_4)_3O\|Y_2Al_5O_{12}$

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We report cw and femtosecond laser operations under diode pumping of a diffusion-bonding heterocomposite Yb-doped crystal: $Yb^{3+}:SrY_4(SiO_4)_3O\|Y_2Al_5O_{12}$(YAG‖SYS:Yb). To show the advantages of this heterocomposite crystal over classical Yb:SYS crystal, we first investigate the high-power cw regime. A cw power of 4.3 W is demonstrated. The femtosecond regime is also investigated, and 1-W-average-power, 130-fs pulses at 1070 nm are produced, which represents, to our knowledge, the first demonstration of an Yb-doped heterocomposite mode-locked laser. © 2005 Optical Society of America

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Ytterbium-doped crystals have led to strong interest in simplifying, compacting, and reducing the cost of ultrashort-pulsed diode-pumped solid-state lasers.[1,2] Nevertheless, the creation of ultrashort (<100-fs) very-high-power (1–100-W) oscillators[3,4] and the quest for ideal crystals for this application[5–8] are still real challenges. Among the potential crystal solutions, $Yb^{3+}:Sr_3Y(BO_3)_3$ (Yb:BOYS) and $Yb^{3+}:SrY_4(SiO_4)_3O$ (Yb:SYS) have been demonstrated to be suitable and interesting from the point of view of developing both highly efficient and ultrashort-pulsed laser sources because of their exceptionally broad and smooth emission spectra.[6–9] In fact, their emission spectra have a similar smoothness to Yb:glass, but they are broader and exhibit cross sections 1 order of magnitude higher. However, in spite of these exceptional spectral properties, which are mainly due to high structural disorder, these crystals have relatively poor thermal properties compared with other Yb-doped crystal, such as Yb:YAG. In fact, the thermal conductivities are 1.5 $W m^{-1} K^{-1}$ for Yb:BOYS and 2.85 $W m^{-1} K^{-1}$ ($\|c$) and 1.3 $W m^{-1} K^{-1}$ ($\perp c$) for Yb:SYS (where c is the optical axis of this uniaxial crystal). Notwithstanding their thermal conductivity, efficient oscillators producing 70-fs pulses have been demonstrated with both Yb:SYS and Yb:BOYS with a diode-pump power of 4 W. Thermal problems begin to occur when one is pumping in the 10-W range.[10] A way to obtain access to this pumping range is to use a composite undoped–doped crystal whose undoped part acts as a heat sink to reduce the temperature in the crystal. The realization of such composite materials by diffusion bonding requires laser quality polishing and thermal treatment with optimized temperature and duration. Yb:SYS could be easily bonded to undoped SYS material, but, in addition, this material would also have the ability to form a heterocomposite with YAG crystal, for instance, which presents higher thermal properties. The SYS crystal belongs to the $P6_3/m$ space group (with cell parameters of $a = b = 0.937$ nm and $c = 0.6873$ nm). For symmetry, the bonding was realized with the SYS crystal oriented with $k\|c$ ($\perp n_o$) (where k is the wave vector) to allow good compatibility between the $k\perp(111)$-oriented YAG and the SYS crystal and to avoid deleterious anisotropic effects such as dilation. After optical contact of the two laser quality polished surfaces [with orientation $\perp$ (111) for YAG and $\perp n_o$ for Yb:SYS], a thermal treatment at 850 °C was applied for 24 h. The temperature of the bonding is low with regard to the melting point of the two laser materials (1970 °C for YAG and 2070 °C for Yb:SYS). This limits the mechanical constraints at the crystal interface. During the 24-h thermal treatment, the surface asperities collapsed, ensuring high contact strength. In this Letter we present the optical results obtained for the original heterocomposite $Yb^{3+}:SrY_4(SiO_4)_3O\|Y_2Al_5O_{12}$ (YAG‖SYS:Yb) crystal. We first demonstrate the advantage of this composite crystal compared with a Yb:SYS single crystal under high-power pumping. Then we demonstrate the possibility of generating high-power femtosecond pulses with this new composite crystal.

Our experiment was performed with a 200-μm core diameter, 0.22-N.A. fiber-coupled laser diode from LIMO emitting up to 13.2 W at 979 nm. The cavity [Fig. 1(b)] is a V-shaped resonator designed to be insensitive to the thermal lens of the crystal.[10] For comparison, we used two 2.8-mm-long 4 mm × 4 mm antireflection-coated crystals (the choice of the same crystal lengths was led by the wish to have similar

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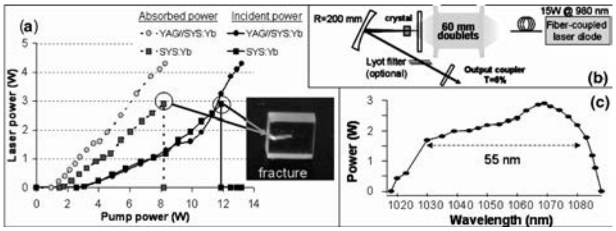

Fig. 1. a, cw laser performance of YAG‖SYS:Yb and Yb:SYS crystals versus absorbed and incident pump power. The photograph shows the fracture in the Yb:SYS crystal. b, Experimental setup for cw operation. c, cw tunability for the heterocomposite crystal at maximum pump power.

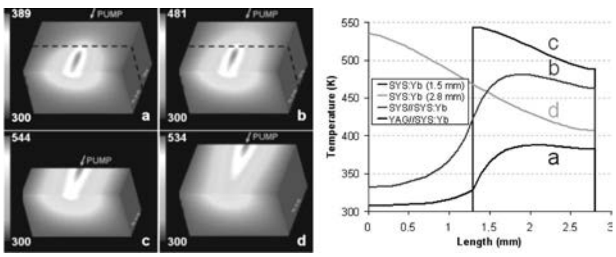

Fig. 2. Left, temperature profiles (obtained with LASCAD software) under 13.2 W of incident pump power (without saturation of absorption) for a, a (1.3+1.5)-mm-long YAG‖SYS:Yb, b, a (1.3+1.5)-mm-long SYS‖SYS:Yb, c, a 1.5-mm-long Yb:SYS, and d, a 2.8-mm-long Yb:SYS. The crystals are pumped by their back side in the figure and the maximum of the scale indicates the maximum of the temperature in the crystal. Right, Corresponding longitudinal temperature profiles in the center of the crystals.

group-velocity dispersions to be able to use the same femtosecond laser cavities). The first crystal was a 5.5% Yb-doped ($8.4\times10^{-20}\ \mathrm{cm}^{-3}$) SYS crystal cut to have $k\perp c$. With this orientation, one can obtain access to the two polarizations corresponding to the two crystallophysic axes of Yb:SYS. The second crystal was a composite YAG‖SYS:Yb crystal made of a 1.3-mm-long undoped YAG crystal and a 1.5-mm-long 5.5% Yb-doped SYS crystal. The crystals were cooled on three edges with a copper mount set at 18°C and a 100-μm-thick indium foil for thermal contact.

In these experimental conditions the Yb:SYS single crystal fractured at 8 W of absorbed (measured under laser operation) pump power. The maximum cw output power for pumping just before fracture was 2.8 W [Fig. 1(a)] with a polarization $\perp c$. However, no fracture appeared for the composite crystal even at full pump power. The maximum laser cw output power was 4.3 W at 1071 nm. To quantify the efficiency of the composite crystal for thermal management, we computed temperature profiles with LASCAD software[11] for different kinds of composite and noncomposite crystals. We then calculated the temperature profiles for the two crystals used in the experiment, e.g., the YAG‖SYS:Yb [Fig. 2(a)] and the 2.8-mm-long Yb:SYS [Fig. 2(d)], but also for two interesting hypothetical crystals for comparison: SYS‖SYS:Yb (1.3 mm of SYS and 1.5 mm of Yb:SYS) homocomposite crystal [Fig. 2(b)] and 1.5-mm-long Yb:SYS [Fig. 2(c)]. These simulations allow us to evaluate—in terms of temperature amplitude and profile—the influence of the nature of the heat sink, with the thermal conductivity of the heat-sink materials being $10.3\ \mathrm{W\,m^{-1}\,K^{-1}}$ for YAG, $2.85\ \mathrm{W\,m^{-1}\,K^{-1}}$ ($\parallel c$) and $1.6\ \mathrm{W\,m^{-1}\,K^{-1}}$ ($\perp c$) for SYS, and $0\ \mathrm{W\,m^{-1}\,K^{-1}}$ for air. At full power the increase in temperature (the edges of the crystal being kept at 300 K) reached 534 K for the Yb:SYS single crystal [Fig. 2(d)] and only 389 K for the composite material [Fig. 2(a)], meaning that temperature gradients (and equivalently stresses) are almost three times less in the composite than in the single crystal. In addition, these temperature simulations clearly indicate (Fig. 2) the preeminence of YAG bonding over the other heat sinks. Moreover, since no separation owing to differences in thermal expansion coefficients between YAG and SYS compounds occurred even at full power, the YAG‖SYS:Yb composite crystal is a good candidate for thermal problem management and would be much more efficient than the homogeneous composite (SYS‖SYS:Yb) for high-power lasers.

Nevertheless, for the development of a femtosecond oscillator the use of heterobonding could raise other problems, such as the heterogeneous nature of the bonding, which could lead to birefringence effects and parasitic reflections. This could strongly affect the femtosecond regime and must be taken into consideration. However, in our case the use of the isotropic YAG crystal should *a priori* allow the problems of depolarization to be reduced. Moreover, the difference in index between YAG (n = 1.82) and SYS (n = 1.77) leads to a low-parasitic Fresnel reflection of 0.02%. To experimentally evaluate the influence of the bonding on the spectrum, we tuned the laser in the cw regime by inserting a Lyot filter in the cavity. A continuous tunability from 1018 to 1088 nm was obtained, and no modulation was observed in the spectrum [Fig. 1(c)].

To generate femtosecond pulses, we inserted a semiconductor saturable absorber mirror (SESAM) and a pair of Gires–Tournois interferometer (GTI) mirrors with $-550\ \mathrm{fs}^2$/bounce [Fig. 3(a)]. The optimal regime was obtained with two bounces on the GTI mirrors, with the beam focused on a 130 μm

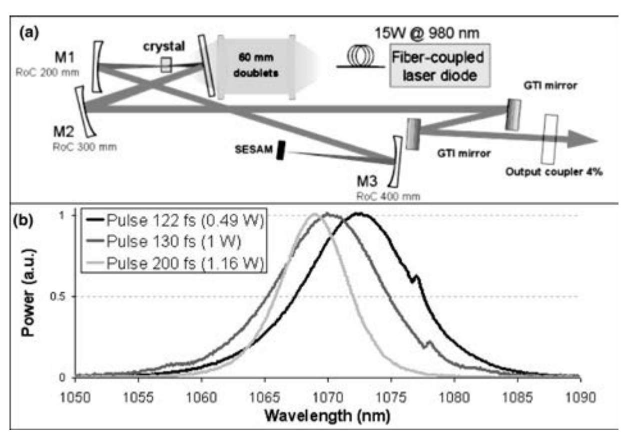

Fig. 3. (a), Experimental setup for the generation of femtosecond pulses. (b), Spectra of 122-, 130-, and 200-fs pulses. RoC, radius of curvature.

$\times 170\ \mu m$ region on the SESAM, and with a 2% or 4% transmission output coupler (OC). The length of the cavity leads to a repetition rate of 77 MHz. Under these conditions and with the 2% OC we obtained 122-fs pulses centered at 1071 nm with an average power of 490 mW (corresponding to an energy of 6.3 nJ/pulse). The spectrum bandwidth was then 10.3 nm. Note that the 490-mW laser power was obtained with 9 W of incident pump power, after which multipulse operation appeared. With the 4% OC we obtained 1 W (for 13 W of pump power) with 130-fs pulses. The energy per pulse was then 13 nJ. The spectrum bandwidth was 9.9 nm. Note that under certain conditions (a wider angle on the GTI mirrors) we could also obtain 200-fs pulses with an average power of 1.16 W. The spectra for these three cases are presented in Fig. 3(b).

Moreover, to demonstrate that the 122-fs pulse duration was not limited by the bonding, we studied the performance of the YAG‖SYS:Yb crystal under the exact experimental conditions as used for the femtosecond mode-locked demonstration with the Yb:SYS single crystal,[8] i.e., in a low-power cavity pumped with a $1\ \mu m \times 100\ \mu m$ 4-W laser diode and with a prism pair to compensate for the intracavity dispersion. The shorter pulses thus obtained had a duration of 100 fs assuming a sech^2 soliton shape (Fig. 4). The corresponding spectrum was centered at 1070 nm with a FWHM bandwidth of 13 nm. The average output power was 70 mW. The YAG‖SYS:Yb femtosecond laser performance has to be compared with the 110-fs pulse duration, and the 420-mW average power obtained with the SYS single crystal must be oriented to be polarized with $k \perp c$. The obtained pulse duration seems to indicate no limitation from bonding. The difference between the pulse durations and the average powers is mainly due to the difference between the Yb-doped SYS lengths (2.8 mm for the single crystal and 1.5 mm for the bonded crystal). In fact, in the case of the longest Yb-doped crystal, the small-signal gain and the average power are higher because of a more important absorbed pump power. In the case of the shortest Yb-doped crystal, the absorption is more saturated, leading to a reduction of the reabsorption effect and to shorter pulses.

In conclusion, we have demonstrated the advantage of the heterocomposite crystal YAG‖SYS:Yb. This new type of material could easily extend the properties of Yb:SYS to higher pump powers. Actually, Yb:SYS exhibits interesting and atypical spectral characteristics among Yb-doped crystals, but this

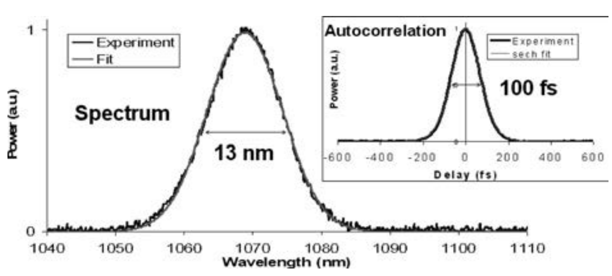

Fig. 4. Spectrum and autocorrelation traces of 100-fs pulses.

compound fractured under classical diode pumping in the 10-W range. We theoretically and experimentally demonstrated the good influence of the heat sink made of undoped YAG. With such a composite crystal, output power of up to 4.3 W was obtained for 8.3 W of absorbed pump power, which was not possible with the Yb:SYS single crystal in the same pumping and cooling configuration. In the femtosecond regime and with high-power diode pumping we obtained up to 1 W of average power with 130-fs pulse duration. These results are to our knowledge the first demonstration of femtosecond mode-locked operation with a heterocomposite Yb-doped crystal. The bonding of different crystals, especially with YAG, is interesting for managing thermal problems. However, such bondings are not easy to obtain with all the studied crystals: For instance, our attempts to bond YAG with BOYS:Yb (another material suitable for femtosecond pulse generation) failed. This made Yb:SYS an even more singular, interesting, and attractive crystal for the development of ultrashort-pulsed high-average-power lasers. The alternative way to obtain higher power with the Yb:SYS (or YAG‖SYS:Yb) would be to use it in a thin-disk design. Since there is no *a priori* incompatibility for using SYS with this technique, this would be an interesting perspective to investigate. The new composite YAG‖SYS:Yb crystal opens new opportunities and has already allowed the shortest pulses ever produced, to our knowledge, in the watt range.

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