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High-power diode-pumped Yb:GdCOB laser: from continuous-wave to femtosecond regime

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We present an efficient tunable continuous-wave diode-pumped Yb^{3+}:$Ca_4GdO(BO_3)_3$ (Yb:GdCOB) laser producing at room temperature up to 3.2 W average power with a slope efficiency of 80% when pumped with a 10 W laser diode. A large tunability from 1017 to 1086 nm is obtained. The broad emission spectrum has been used to develop a diode-pumped Yb:GdCOB femtosecond laser. The laser generated 90 fs pulses,at a center wavelength of 1045 nm. By using a semiconductor saturable absorber mirror (SESAM) for the mode locking, the average power was 40 mW and the repetition rate of 100 MHz.

1. Introduction

Ytterbium-doped crystals have a wide potential of application in the development of efficient diode-pumped lasers. Thanks to their simple quasi-three-level electronic structure, based on two electronic manifolds [1–4], they are very suitable for high-power diode pumping. Firstly, the low-quantum defect reduces the thermal load and allows a very efficient optical–optical conversion from the pump power to the laser. Secondly, the absence of additional parasitic levels higher than the first excited state of this rare-earth avoids undesired effects such as excited-state absorption and up-conversion. Thus, these properties added to the development of high-power InGaAs laser diodes make ytterbium-doped materials very interesting. Another advantage of ytterbium compared to others dopants such as neodymium is its broadband nature which is very suitable for both tunable and ultrafast lasers.

However, the main problem of ytterbium as a dopant is its quasi-three-level nature. In fact, because of the thermal population filling of the lower laser levels, the performance of the ytterbium laser

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strongly depends on the temperature. Operating this laser at room temperature then often leads to a sacrifice in efficiency, or in average output power. When the absorbed pump power is high and thermal load is increased, the efficiency of the laser drastically decreases. That is why, in the point of view of reducing the thermal effects, the choice of the host matrices is very important for diode-pumped Yb lasers.

In this paper, we present the results obtained with Yb^{3+}-doped $Ca_4GdO(BO_3)_3$ (Yb:GdCOB) materials. This recently discovered crystal [5–7] belongs to the calcium rare-earth oxoborate family. It can be doped by ytterbium ions by substituting the Gd rare-earth ions. The doping in Yb^{3+} can be very high (up to 30%) due to the lanthanide site in the oxoborate structure, and the absence of quenching concentration. In our case, we used a 15%-doped Yb:GdCOB crystal. The high concentration allows a short pump-absorption length in the crystal which is an advantage when it is pumped with a non-diffraction-limited beam from a high-power laser diode.

Moreover, Yb:LnCOB ($Ln = Gd, Y$) crystals also exhibit more inherent properties which are interesting for efficient, largely tunable laser sources. First, they have a very broadband emission spectrum (43 nm FWHM) (Fig. 1), compared to other crystals such as, for example, the Yb:YAG (12 nm FWHM). Secondly, this crystal, in comparison to glasses, has a relatively good thermal conductivity ($k = 2.1$ W m^{-1} K^{-1} for the GdCOB compared to 0.7 W m^{-1} K^{-1} for glasses). The thermal conductivity is a very important parameter for quasi-three-level media because it directly influences the temperature of the gain area and thus the thermal population at the lower laser level. Furthermore, Yb:GdCOB crystals can be diode pumped in their zero-line peak wavelength at 976 nm leading to a quantum defect of only 7% (Fig. 1). Thanks to their large splitting of ${}^2F_{7/2}$ Stark levels – 1003 cm^{-1} compared to 628 cm^{-1} in the Yb:YAG-, the temperature less affects the thermal population in the Yb:GdCOB crystals. The Yb:GdCOB crystals combine the advantages of a broadband emission which is comparable to the one of Yb-doped glasses to the relatively good thermal conductivity of a crystal.

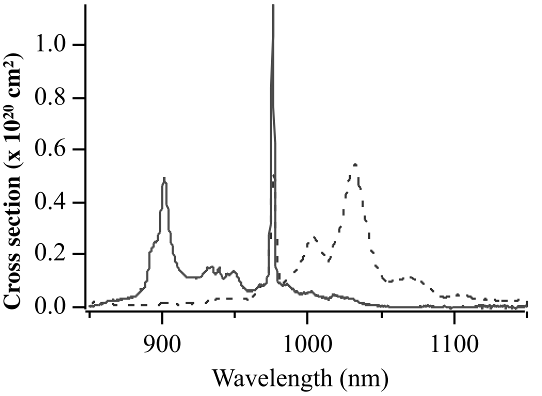

Fig. 1. Yb:GdCOB emission and absorption spectra (solid line: absorption spectrum, dashed line: emission spectrum).

2. Performance of a Yb:GdCOB crystal longitudinally pumped on both sides by two single stripe laser diodes

The first experiment consisted in optimizing the performance in a stable cavity with a longitudinally pumped Yb:GdCOB crystal (Fig. 2). It was performed with two high brightness laser diode emitting 1.6 W at 976 nm with an emitting area of 1 × 100 μm^2. The first diode (diode 1) was collimated by a 15-mm objective, and then, reshaped by a 8× cylindrical telescope, in its slow direction, and finally focused by a 60-mm doublet. The incident pump power on the crystal after the dichroic mirror (DM_1) was 1.1 W. A second 1.6-W diode (diode 2) was used to pump the crystal on its second side (Fig. 2). This diode which included a

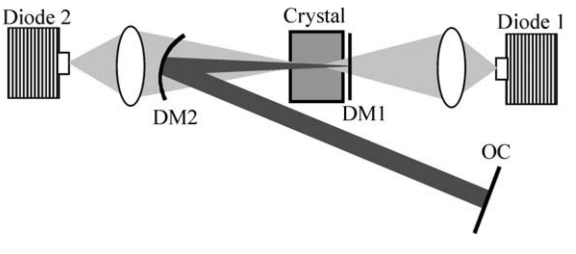

Fig. 2. Experimental setup. DM: Dichroic mirrors, high transmission at 976 nm, high reflection between 1020 and 1100 nm. DM1: plan mirror; DM2: 100-mm curvature radius mirror. OC: output coupler.

collimating fiber lens, was re-collimated by a 140-mm doublet, and focused by a 100-mm doublet. The incident power on the crystal after the dichroic mirror (DM_2) was 0.9 W. To optimize the absorption length in this double side pumping, a 4-mm, 15%-doped Yb:GdCOB crystal AR coated on both sides was used. In these conditions, the total absorption pump power was 1.3 W.

Fig. 3 shows the results obtained at room temperature with a 2%, and a 4% transmission output coupler (OC). The maximum slope efficiency of 77% was obtained with the 2% OC mirror. With this mirror, a maximum average output power of 814 mW at 1050 nm was obtained for 1.3 W of absorbed pump power corresponding to a 63% optical–optical conversion [8]. This was obtained without any cooling of the crystal which indicates the good thermal behavior of this crystal even at high-average pump power.

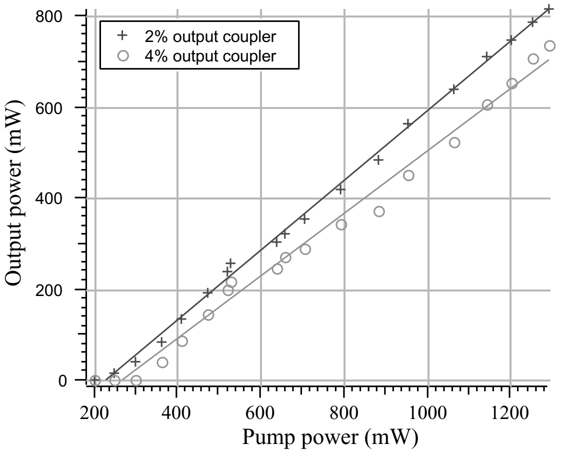

Fig. 3. Output power of the laser versus absorbed pump power for the double-side pumped 15%-doped Yb:GdCOB laser emitting at 1050 nm.

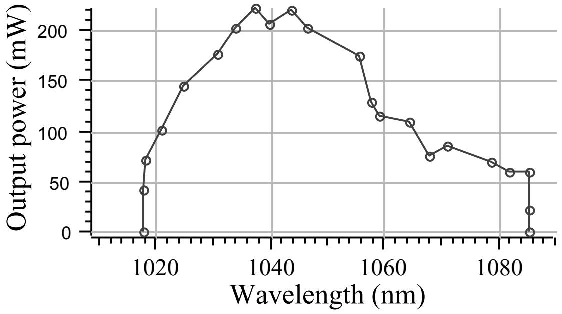

Fig. 4. Tunability of the CW Yb:GdCOB laser diode pumped at 976 nm.

To estimate the tunability of this source, we inserted a prism in the collimated arm (DM_2–OC in Fig. 2). In this case, we used only the pump diode 1, the length of the 15%-doped Yb:GdCOB crystal was reduced to 3 mm and the transmission of the OC was 4%. As shown in Fig. 4 the tunability was very broad: from 1017 to 1086 nm with a FWHM of 44 nm limited in the short wavelengths by the cutoff due to the mirrors coating.

3. Development of a high-power CW Yb:GdCOB laser pumped by a fiber-coupled high-brightness diode laser array

As we have not seen limitations in the laser output power in the previous experiment based on two single stripe pumping diodes, we decided to pump our crystal with a high-power laser array. We used a 10 W fiber-coupled high-brightness laser diode (OPC-D010-976-HB250 from OptoPower. The core diameter was 250 μm, the numerical aperture was 0.2 and the M^2 factor of the beam was measured to be 77. The diode emission wavelength was temperature tuned to 976 nm. The beam was collimated with a 60-mm focal length doublet and focused onto the crystal with an identical doublet. The pump spot size (250 μm in diameter) allows the crystal length to match the confocal parameter of the pump beam. The pump intensity $I_p = 18.1$ kW cm^{-2}) was higher than the pump saturation intensity ($I_{psat} = 8.7$ kW cm^{-2}) showing that the ground state was depleted under unlasing conditions. This is important for quasi-three-level lasers since it prevents reabsorption losses.

We used the same 3-mm long 15%-doped Yb^{3+}:GdCOB crystal in this experiment, but in this case the temperature of the crystal surrounding was maintained at 10 °C with a thermoelectric cooler.

The spectral linewidth of the diode was 3 nm (FWHM), close to the Yb:GdCOB zero-line absorption linewidth ($\Delta\lambda = 2.5$ nm FWHM). We measured an unsaturated absorption coefficient $\alpha = 4$ cm^{-1}. At maximum pump power and under

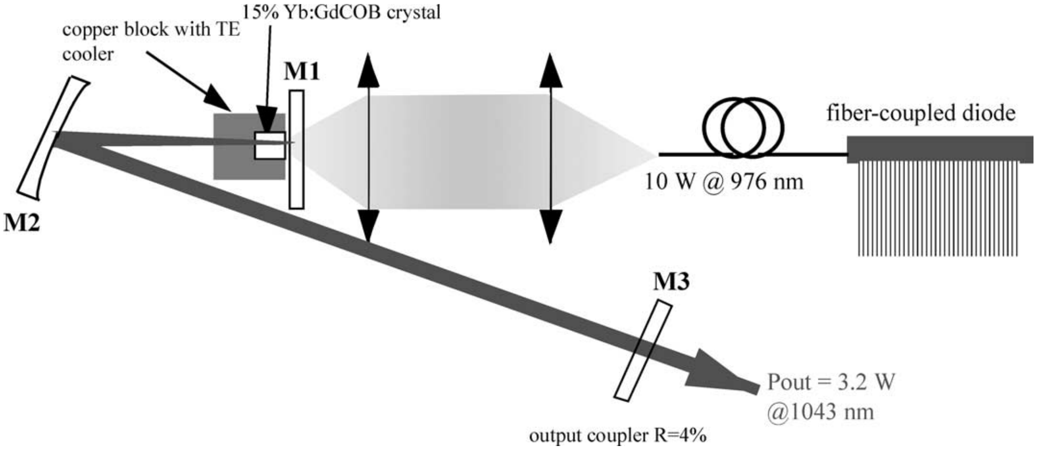

Fig. 5. Experimental set-up of the high-power diode-pumped Yb:GdCOB laser.

lasing conditions, the crystal absorbed 5.2 W (58% of the incident power), resulting in an absorption coefficient equal to 3 cm^{-1}.

We tested two cavity designs: the first one provided the highest power and was easy to align, but the laser beam was slightly multimode. The second cavity supported a diffraction-limited beam (TEM_{00}), but with less power.

The first cavity (Fig. 5) was composed of a plane dichroic rear mirror M_1 (HT @ 980 nm, HR over 1030–1100 nm), a folding concave HR mirror M_2 (radius of curvature = 200 mm) and a plane OC M_3. We performed several experiments with various OC transmissions: 0.5%, 1%, 4.2%, 5%, 6.15% and 8% (at 1040 nm). The best performances were achieved with the 4.2% mirror, so that only the results obtained with this mirror are presented in the following.

A maximum output power of 3.2 W at 1043 nm was obtained in a slightly multimode beam ($M^2_x = 2.8$, $M^2_y = 3.1$). This was due to the not perfect matching between pump and cavity modes (the cavity waist radius was 64 μm, whereas the pump waist radius was 125 μm).

The laser threshold was 570 mW, and the slope efficiency with respect to the absorbed pump power reached 81%. The optical–optical efficiency, with respect to the diode power was 32%, resulting in an electrical–optical efficiency of 11% (Fig. 6). The absorbed pump power has been measured for each point under lasing conditions.

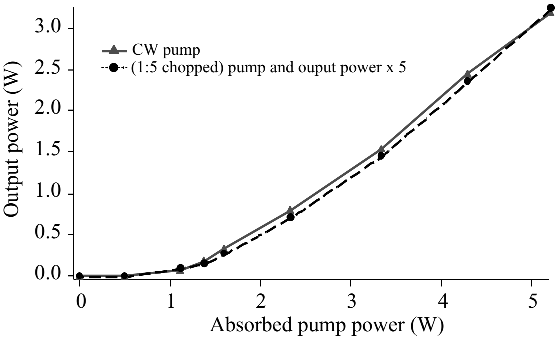

Fig. 6. CW output power versus absorber pump power (solid curve) with a 4.2% transmission OC. Dashed curve: quasi-CW pumping, the power is measured during the pumping window (see text).

To demonstrate the absence of thermal limitations, we mechanically chopped the pump beam with a duty cycle of 1:5 in order to decrease the average induced thermal load within the crystal. The experiments in the quasi-CW regime were performed with a calibrated photodiode, in order to measure the power only whenever steady state is reached within a cycle. We obtained slightly the same results in CW and quasi-CW regime, showing that thermal effects are not a limitation in our case (Fig. 6).

As in previous experiments, we measured a tunability from 1018 to 1086 nm, with more than 1 W of output power over a bandwidth of 30 nm.

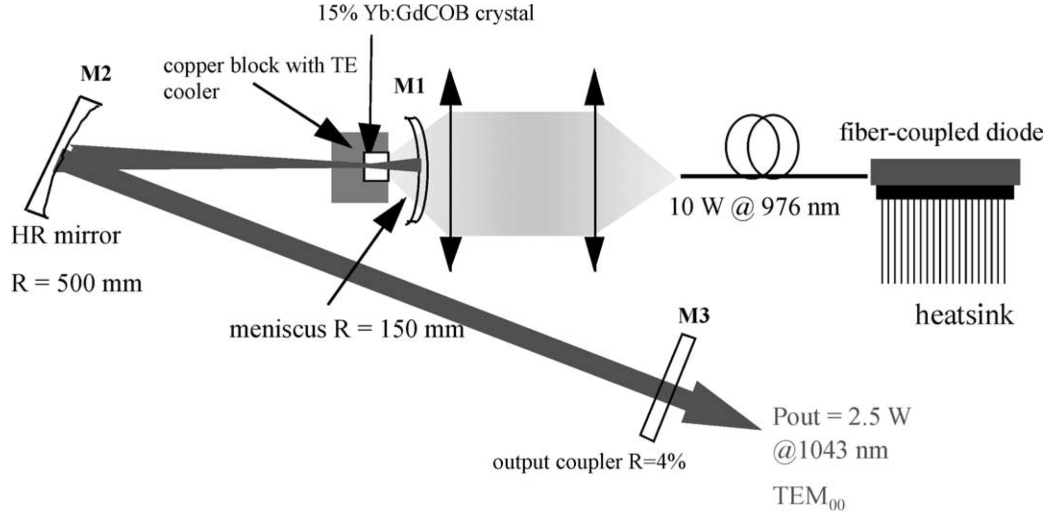

Fig. 7. Improved laser cavity design used to achieve a diffraction-limited output beam.

In order to improve the beam quality of the laser, we changed the design of the cavity. The TEM$_{00}$ mode size was increased to better match the pumped area in the crystal, whereas the pump optics remained unchanged. We replaced the plane mirror M$_1$ by a 150-mm radius of curvature meniscus (HT @ 980 nm and HR over 1020–1100 nm). The M$_2$ mirror was replaced by a 500-mm radius of curvature concave mirror (see Fig. 7). The OC M$_3$ remained the same (4% transmission). The cavity mode waist radius was then 120 μm, whereas the pump mode waist radius was 125 μm, so that only the TEM$_{00}$ mode could be excited. In this case, we obtained a maximum output power of 2.50 W, in a diffraction-limited beam. We measured a quality factor $M^2_x = 1.11$ in the horizontal direction and $M^2_y = 1.12$ in the vertical direction. Since the pump and cavity beams had to be perfectly colinear inside the crystal in order to extract the maximum pump power, this cavity was naturally much more difficult to align than the previous one.

3.1. Femtosecond diode-pumped Yb:GdCOB laser

Ytterbium-doped materials generally exhibit a broad emission band, compared to neodymium-doped crystals for example. This properties is 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 Yb-doped glass matrices [9,10]. The shortest pulse duration reported for an Yb-doped laser based on a crystalline matrix was 340 fs using Yb:YAG [8]. 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 smaller emission cross-sections compared to crystals. For example, in the case of Yb:phosphate glasses the emission cross section is 0.05×10^{-20} cm^2 (at 1060 nm) with a bandwidth of 62 nm compared to an emission cross section of 2×10^{-20} cm^2 and a bandwidth of 12 nm for Yb:YAG. Yb-doped glass materials have also a lower thermal conductivity, this leads to serious heat load problems for high-average power operation and significantly lower small signal gain and laser efficiency. Slope efficiencies of 49% for a Yb:phosphate glass laser [11] were obtained in contrast to 80% with Yb:YAG in CW operation [12]. In addition, the small emission cross-sections of Yb-doped glasses require a more careful design of the laser parameters in passively mode-locked operation in order to suppress Q-switching instabilities in the mode-locked pulse train [13]. 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.

With this respect, we found that Yb:GdCOB crystal has favorable properties (fluorescence bandwidth and thermal properties) for the generation of femtosecond pulses. In this section, we will report the experiments performed on a femtosecond diode-pumped Yb:GdCOB laser.

The experiment was carried out with a 3-mm long, 15%-doped, AR-coated Yb:GdCOB crystal cut along its crystallophysic axis. The pumping system was a 2-W, 1×100 μm^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× cylindrical telescope and finally focused in the crystal with a 30-mm lens. In this configuration, the measured pump beam waist was 20×70 μm^2. The crystal absorbed only 580 mW of pump power because of the broad emission of the diode (about 6 nm) compared to the absorption band of the Yb:GdCOB crystal (2.3 nm). The laser cavity design is shown in Fig. 8. To produce short pulses, a low-finesse semiconductor saturable absorber mirror (SESAM) [14] was used together with soliton-shaping processes. The absorber consisted of a double quantum well structure which resulted in a modulation depth of about 0.7%. The parameters of the cavity have been optimized in order to avoid the Q-switched mode-locking regime which is an important issue in ytterbium-doped lasers whose gain is relatively low [13]. The beam waists were set at around 45 μm on the SESAM and 70 μm in the crystal. A pair of SF10 prisms separated by 30 cm compensates for the positive dispersion inside the cavity and balances the self-phase modulation introduced by the Kerr non-linearity of the laser crystal in order to form soliton-like pulses.

In this cavity, a CW mode-locking regime was obtained with a stable pulse train at 100 MHz repetition rate. The average output power was 40 and 60 mW with, respectively, 1% and 2% transmission OCs. The relatively poor efficiency

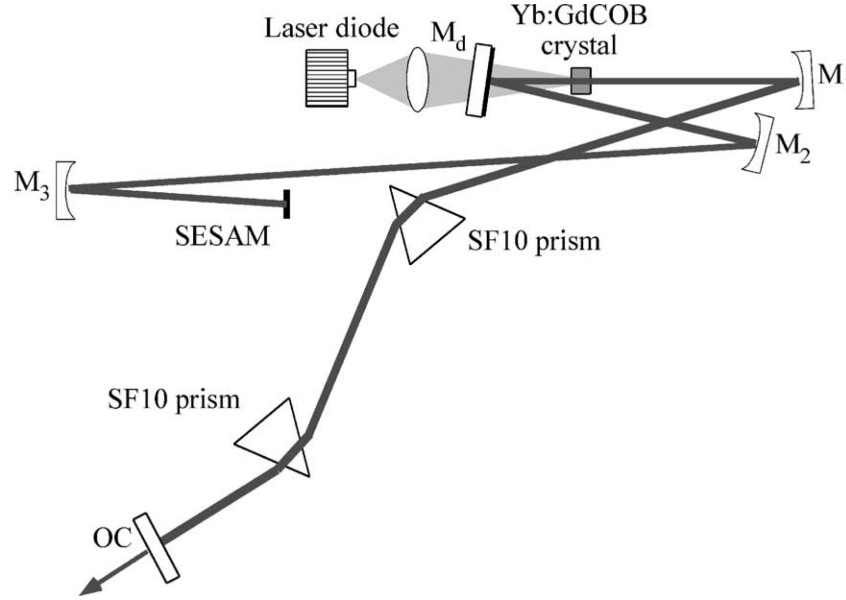

Fig. 8. Experimental setup. M_d: dichroic mirror; M_1, M_2, M_3: HR mirrors with, respectively, 30-mm, 20-mm, and 15-mm radius of curvature; OC: 1% or 2% transmission plane output coupler; SESAM: high-finesse SESAM.

of this laser compared to the CW results [8] is mainly due to two factors. First, the large bandwidth of the pump has a poor overlap with the absorption spectrum. Secondly, the prisms we used exhibited large losses. The pulse duration was measured with a background free second-order autocorrelator. Fig. 9 shows the autocorrelation trace obtained with a 1% OC 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. 10, exhibits a FWHM bandwidth of 14.7 nm around 1045 nm which gives a time-bandwidth-product ($\Delta\tau.\Delta\nu$) of 0.36 [15]. This is close to the Fourier transform limit of 0.32. Using a 2% OC we obtained 60 mW average output power at a slightly longer pulse duration of about 100 fs.

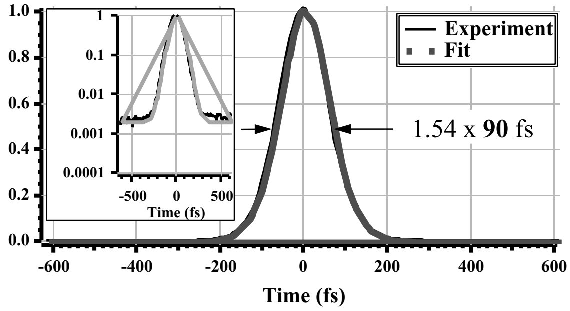

Fig. 9. Intensity second-order autocorrelation trace (solid line) of the 90 fs pulses and its fit (dashed line) considering a sech^2 intensity profile. Inset graph: same graph with a logarithmic scale.

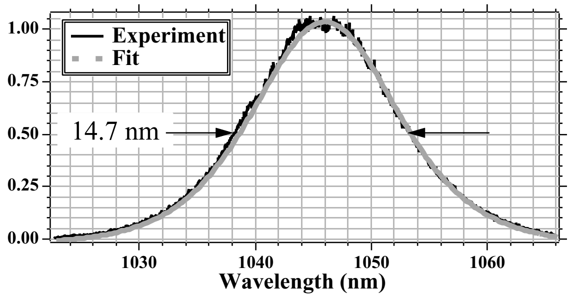

Fig. 10. Spectrum of infrared the 90 fs pulses.

4. Conclusion

In conclusion, we have demonstrated that the new crystal of Yb:GdCOB is a suitable material for the development of high-power CW lasers. We have obtained up to 3.2 W at 1040 nm with an absorbed pump power of 5.2 W, providing an optical efficiency of 32%. With a slightly different cavity we obtained 2.5 W in a TEM_{00} mode, thus providing an optical efficiency of 25%. A large tunability from 1018 to 1086 nm has been obtained.

Furthermore, due to its broad emission band, this crystal is well suited for the development of all solid-state diode-pumped femtosecond lasers. We have demonstrated the feasibility of an oscillator producing 90 fs pulses under diode pumping. In the future, our work will concern development of a high-energy femtosecond laser chain based on the Yb:GdCOB crystal.

Acknowledgements

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