Diode-pumped efficient laser action of Yb^{3+}:LYSO crystal

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Effective diode-pumped continuous wave (CW) tunable laser action of a new alloyed crystal Yb:LYSO is demonstrated. The alloyed LYSO crystal possesses the desirable physical and laser performance of La_2SiO_5 (LSO), as well as the favorable growth properties and costs of Y_2SiO_5 (YSO) in the same time. With a 5 at.-% Yb:LYSO sample, the output power of 2.84 W at 1085 nm and an optical-to-optical conversion efficiency of 54.5% are achieved. Its laser wavelength can be tuned over a broad range of 81 nm, from 1030 to 1111 nm.

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Yb^{3+}-doped laser systems have received increasing attention since the rapid development of high power and high brightness laser diodes emitting at 900—980 nm in latter 1990s, and have been expected to be the most potential alternatives to the Nd^{3+}-doped ones in the near infrared (IR) spectral range. Yb^{3+} ion has only two electronic multiplets (the ground state $^2F_{7/2}$ and the excited state $^2F_{5/2}$), which induces a simple electronic-level scheme, and contributes to a low intrinsic quantum defect, a weak thermal load, an absence of luminescence quenching, and an enhanced laser action. Compared with Nd^{3+}-doped materials, Yb^{3+}-doped ones have broader absorption and emission spectra owing to the strong electron-phonon coupling[1]. In addition, Yb^{3+}-doped materials possess longer radiative lifetimes of the upper laser manifolds, which lead to increased energy-storage property and are favorable for enhancing the economic utilization of the diode pumps. Various interesting results have been reported for continuous-wave (CW) or mode-locked operations based on the diode pump with Yb^{3+}-doped materials during the past decade, such as garnet Yb:YAG[2−4], borate Yb:YAB[5], vanadate Yb:YVO_4[6], tungstates Yb:KGW and Yb:KYW[7−9], and oxyorthosilicate Yb:YSO[10]. Recently, single-crystal growth of Yb:LSO by the Czochralski technique has been well documented, and their optical and physical properties have been evaluated and discussed in previous work[11].

Although Yb:LSO crystal exhibits excellent laser performances and good mechanical properties, technology for its large scale crystal growth is less mature than that for Y_2SiO_5 (YSO). It is primarily limited by the higher melting point of ~ 2150 °C for La_2SiO_5 (LSO), which is relatively higher than ~ 1980 °C for YSO and very close to the breakdown temperature of iridium crucible and insulating material of ZrO_2. Furthermore, the lutetium oxide is relatively expensive. Cerium-doped alloyed crystals, such as Ce:LYSO, exhibiting significant scintillator properties of LSO along with the growth characteristics and costs associated with YSO, has been grown successfully[12,13]. In addition, in our previous work, we have alloyed the Yb-doped GSO with YSO to generate the mixed crystal of Yb:GYSO successfully[14]. So we speculate that alloying Yb-doped LSO and YSO would produce an attractive substitute with low cost for Yb:LSO, and combine the prominent laser performance of Yb:LSO with the growth advantages of Yb:YSO together. Furthermore, as a mixed crystal, LYSO has more disordered structure than YSO or LSO. So it can be expected that the full-width at half maximum (FWHM) of LYSO should be larger than that of LSO or YSO, which is more advantageous for producing broadly tunable and ultra-short lasers.

In this paper, we present a new material, Yb:LYSO, for the purpose of reducing the costs and improving the growth characteristics while remaining advantageous laser properties of Yb:LSO. Although the study on Yb:LYSO is still in elementary period, experimental results confirm that the method of combining the high laser performance of Yb:LSO with good growth properties of Yb:YSO is effective and low-cost. The efficient CW tunable Yb:LYSO laser action was demonstrated, and the broadest tunable range for Yb:LYSO was achieved.

The alloyed Yb:$Lu_{2(1-x)}Y_{2x}SiO_5$ ($x = 0.5$) crystal was grown by Czochraski method from a 50/50 solution of LSO and Y_2SiO_5 (YSO) in inductively heated iridium crucibles, with the dopant Yb^{3+} of 5 at.-%. It has the same C2/c structure as LSO and YSO, and the melting point for LYSO is estimated to be ~ 2000 °C. The fluorescence lifetime value of the excited manifold $^2F_{5/2}$ of Yb^{3+} has been measured to be 1.80 ms by exciting the samples with a xenon lamp and detected by an S-1 photomultiplier tube. This favorable lifetime could increase the economic utilization of the costly pump power. The unpolarized absorption spectrum of 5 at.-% Yb:LYSO is illustrated in Fig. 1, which was recorded by a Jasco V-570

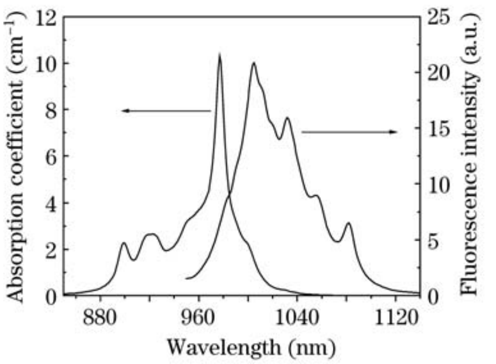

Fig. 1. Room-temperature unpolarized absorption and emission spectra of Yb:LYSO laser crystal.

UV/VIS/NIR spectrophotometer at room temperature. From it, we can see that the absorption spectrum curve is mainly composed of one strong band around 977 nm, and other two weak absorption bands around 899 and 923 nm. Apparently, the absorption peak around 977 nm belongs to the zero-line transition between the lowest levels of $^2F_{7/2}$ and $^2F_{5/2}$ manifolds. Others correspond to the typical transitions from the ground state $^2F_{7/2}$ to other sublevels of $^2F_{5/2}$ of Yb^{3+} in LYSO host. The absorption peak at 977 nm is well matched with the emission wavelength of commercially available high-power InGaAs laser diodes. The IR fluorescent spectrum of Yb:LYSO excited under the InGaAs laser diode (LD) source with the wavelength of 940 nm at room temperature is also presented in Fig. 1. The fluorescence curve mainly includes four bands around 1005, 1033, 1058, and 1082 nm, corresponding to the transitions from the lowest level of $^2F_{5/2}$ to the other levels of $^2F_{7/2}$ manifold except the lowest one. The broad emission spectrum is favorable for the development of new broadly tunable laser sources, femtosecond oscillators and amplifiers. From the energy-level diagram, we can estimate the overall splitting of $^2F_{7/2}$ manifold reaches about 993 cm^{-1}. Large fundamental manifold splitting promises low pump threshold laser operation, for reabsorption losses at emission wavelengths can be decreased due to low thermal population of the terminal laser level. Therefore, in Yb:LYSO laser, laser performance of low threshold is suggested because of its relatively large splitting.

The basic outline of the CW Yb:LYSO laser setup is shown in Fig. 2. The resonator consisted of one dichroic input coupler mirror M$_1$ (high-transmission at 976 nm and high-reflection at 1030—1170 nm), one folding mirror M$_2$ (high-transmission at 976 nm and high-reflection at 1030—1170 nm), and one output coupler (OC), and it was a stable three-mirror folded cavity supporting only TEM$_{00}$ mode. The input mirror M$_1$ and output coupler were both flat, and the curvature radius of the folded mirror M$_2$ was 300 mm. The 5 × 5 × 3 (mm), 5 at.-% Yb:LYSO sample was wrapped with indium foil and mounted in a water-cooled copper block, uncoated and polished with parallel end surfaces. The water temperature was maintained at 14 °C to prevent thermal fracture. In order to realize the laser operation in TEM$_{00}$ mode and result in high conversion efficiency, the lengths of two arms were configured to keep the mode matching in crystal between the pump beam and the fundamental resonant mode, and the total cavity length was about 70 cm. A fiber-coupled diode laser, with a core-diameter of 200 μm, a numerical aperture of 0.22, and maximum output power of 10 W, emitting at the wavelength range of 975—978 nm was used as the pump source. To keep the maximum absorption, the operating wavelength was tuned by temperature of diode to match the peak absorption of the crystal. The pump beam was image-relayed to the crystal with a ratio of 1:1, and the pump radius in the crystal is $\sim$ 100 μm.

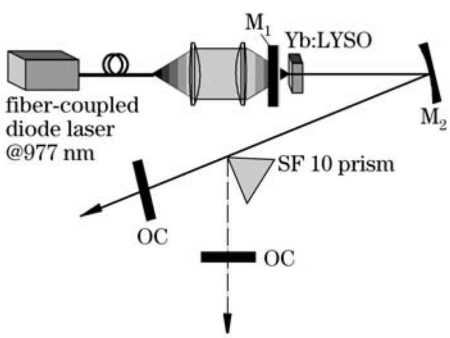

Fig. 2. Configuration of the CW Yb:LYSO laser.

For Yb:LYSO laser, we used output couplers with different transmissions to obtain the optimum output. Figure 3 shows the CW laser output power as a function of the absorbed pump power with different output couplers. For output transmissions of T = 1.5%, T = 4%, T = 5% and T = 7%, corresponding laser thresholds are about 0.41, 0.56, 0.74, and 0.86 W, respectively. At absorbed pump power of 5.21 W, maximum laser output power of 2.84 W at 1085 nm without tuning was obtained with a 5% transmission output coupler. Under lasing condition and at maximum power, the uncoated crystal absorbed about 70% of the incident pump power, and the optical-to-optical conversion efficiency researched 54.5% with respect to absorbed pump power. The fluorescence intensity of peaks decreases along the longer wavelength side in the emission spectrum. However, considering the corresponding terminal laser level of each band is decreasingly populated along the longer wavelength, laser actions around the peak of 1082 nm demonstrate low laser threshold and high conversion efficiency.

The wavelength tuning for Yb:LYSO laser fulfilled by inserting an SF 10 dispersive prism in the collimated arm

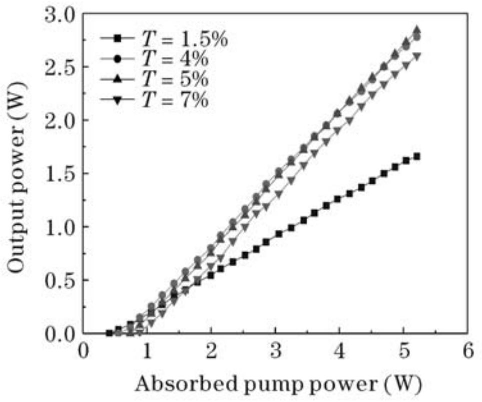

Fig. 3. Output power versus absorbed pump power with 5 at.-% Yb:LYSO for different output couplers at 1085 nm.

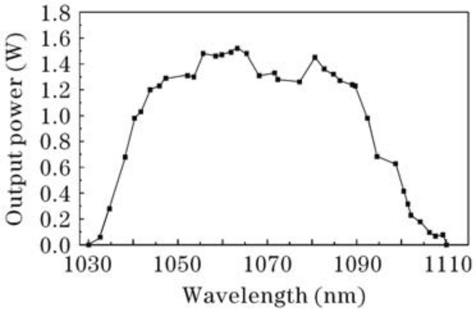

Fig. 4. Tuning curve of Yb:LYSO with an SF 10 dispersive prism and a 4% transmission output coupler.

of the laser cavity is shown in Fig. 2. Output coupler with 4% transmission was chosen for efficient tuning output, instead of the optimum output coupler of 5% for no tuning cavity, because the insertion of the prism increased the intracavity losses. The wavelength tuning with horizontal polarization of Yb:LYSO is illustrated in Fig. 4. With absorbed pump power of 4.7 W, the Yb:LYSO crystal could support a broad continuous range of 81 nm, from 1030 to 1111 nm. To our knowledge, this is the broadest tunable range ever obtained from Yb:LYSO laser, and it is broader than that of either Yb:LSO or Yb:YSO in Ref. [9]. We attribute the broader tunability of Yb:LYSO crystal to the merit of being a mixed crystal, which provides LYSO crystal more disordered structure than that of YSO or LSO, hence the excellent tunable capability. The wavelength tuning curve of Yb:LYSO is flatter and smoother with fewer fluctuations. And it sustains a range of 52 nm over 1.0 W, from 1040 to 1092 nm. And these results make more potential for the use of Yb:LYSO in the development of all-solid-state tunable CW and femtosecond lasers for shorter pulse duration. In our experiment, further tuning on shorter wavelength under 1030 nm is limited by the coating of our input coupler. Therefore, it always resonated at its vicinal emission peak of 1030 nm with worse beam quality when the laser was tuned to shorter wavelength. In addition, when combining our experiment results with the former one[15], in which the Yb:LYSO laser can be tuned to the shorter wavelength of 1014 nm, Yb:LYSO is promising to sustain a broad tunable range of about 100 nm if the dichroic coating of cavity mirrors is selected properly.

In conclusion, to maintain the excellent laser performance of Yb:LSO crystal, improve growth characteristics, and reduce costs, we grew Yb:LYSO crystal for an attractive substitute and investigated its laser action. Grown by Czochralski method, Yb:LYSO has some attractive merits, such as reduced melting point, longer crucible lifetime, and lower cost of starting material. In a word, it retains excellent laser properties of LSO with reduced growth cost, as well as the favorable growth properties of YSO. With the 5 at.-% Yb:LYSO sample, 2.84-W output power at 1085 nm was achieved with an optical-to-optical conversion efficiency of 54.5%. The laser wavelength could be tuned from 1030 to 1111 nm continuously, which is the broadest range ever achieved from Yb:LYSO laser. Owing to its broadly flat wavelength tuning range, it is also favorable to be used for a mode locked laser operation. In consequence, Yb:LYSO offers an promising alternative for efficient, low-cost, broadly tunable diode-pumped lasers, although researches on it are still elementary. Currently we are working on the growth of a series of Yb:$\mathrm{Lu}_{2(1-x)}\mathrm{Y}_{2x}\mathrm{SiO}_5$ ($x = 0 - 1$) crystals and their laser performances. We believe that, by choosing the most appropriate value of x, more interesting results will be demonstrated, and Yb:$\mathrm{Lu}_{2(1-x)}\mathrm{Y}_{2x}\mathrm{SiO}_5$ could be one of the most excellent laser crystals for achieving high-power diode-pumped broadly tunable CW or mode locked lasers.

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