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A highly efficient, compact Yb:KYW laser for mobile precision systems

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Abstract. **We have developed a promising scheme of a multimode-diode-pumped ytterbium laser. The Yb:KYW laser in the cw regime demonstrates record-high differential (40 %) and total optical (35 %) efficiencies. Mode locking is realised, which allows the scheme to be used for the development of compact laser systems, such as mobile femtosecond precision synthesisers. The peculiarities of the laser operation and ways of further improving its efficiency are discussed.**

Keywords: *ytterbium laser, diode pumping, mode locking, ultrashort pulses.*

1. Introduction

Optical frequency synthesisers based on femtosecond lasers (femtosecond synthesisers) are the most important units of precision laser systems used for measuring absolute optical frequencies and their stability [1]. They can also solve the problem of the transfer of frequency characteristics of optical frequency standards to the radio frequency range. Currently, synthesisers based on femtosecond erbium-doped fibre lasers are becoming more popular [2]. Compact design and stability of the characteristics make fibre lasers promising for the fabrication of mobile synthesisers. Another candidate for the development of such synthesisers is a solid-state femtosecond laser that can be directly pumped by diode lasers. The most attractive here are ytterbium-doped crystals [3–6]. The radiation wavelength of the lasers based on such crystals is 1.03–1.06 μm. Ytterbium-doped crystals have absorption bands which coincide with the wavelength range of high-power semiconductor diode lasers. Among the gain media doped with ytterbium, potassium tungstate crystals [$KY(WO_4)_2$:Yb^{3+}(Yb:KYW) and $KGd(WO_4)_2$:Yb^{3+}(KGW:Yb)] [6] are among the most promising due to their large cross sections of absorption and stimulated emission, broad band luminescence and relatively high thermal conductivity. However, commercial synthesisers based on ytterbium-doped gain media are not available. The known optical systems are not suitable for the development of specific femtosecond lasers used in the mobile precision systems. To this end, compact stable lasers with an intermode frequency of more than 100 MHz and high efficiency are needed. Thus, the development of femtosecond lasers with an ytterbium-doped gain medium for mobile precision systems, including femtosecond synthesisers, is undoubtedly important.

Known are a number of publications devoted to the studies of ytterbium lasers pumped by free space and fibre-pigtailed diode lasers in free and femtosecond regimes. In this case, use was made of multimode diode pumping (see, for example, [7–12]). The femtosecond regime was usually achieved by employing a semiconductor saturable-absorber mirror (SESAM). Only Lui et al. [8] obtained this regime without a SESAM, but lasing was very critical to cavity tuning. Lasers with a pulse repetition rate (intermode frequency) of less than 100 MHz were investigated. Klenner et al. [12] described a laser with a pulse repetition rate of 1 GHz, a slope efficiency $\eta_{\rm dif}$ = 34% at an output power of 3.4 W (total optical efficiency $\eta_{\rm opt}$ = 26%). Femtosecond pulses were generated at a pump power over 7.2 W.

Known are the results of studies of ytterbium lasers pumped by low-power single-mode free-space and fibre-coupled diode lasers [13–19] (at a power of less than 1 W in the cw regime). Pumping is performed by one or two diode lasers. The average output power of such femtosecond ytterbium lasers lies in the range from tens to hundreds of milliwatts. Stable lasing occurs both by using a SESAM and without it. Compact, single-mode diode-pumped femtosecond lasers have been developed, which can be operated at a pulse repetition rate greater than 1 GHz and $\eta_{\rm dif}$ = 69% with an output power of 770 mW ($\eta_{\rm opt}$ = 61%) [18]. Endo et al. [19] used this pumping to obtain a pulse repetition rate of 4.6 GHz.

Thus, relatively high-power (with a power greater or about 1 W) ytterbium lasers in free and femtosecond regimes have been realised only for the case of multimode diode pumping with non-diffraction-limited beam divergence. In this case, the intermode frequency of ytterbium lasers is usually less than 100 MHz, i.e., their dimensions are large enough and are not suited for the development of small-scale mobile laser systems. The laser with an intermode frequency of 1 GHz described in [12] had a high lasing threshold (2.1 W). Optimal schemes of ytterbium lasers for their use in compact precision laser systems (e.g., optical frequency synthesisers) have not been studied and discussed in the literature.

Recently, Fiebig et al. [20] developed a single-mode DBR tapered diode laser with a power up to 12 W in the cw regime. The use of such a laser made it possible to obtain lasing in an ytterbium laser with an average output power up to 2.2 W and a pulse repetition rate of 1 GHz [21, 22]. Stable and self-starting regimes were obtained using SESAM-soliton-mode locking. However, such high-power single-mode pump lasers are still at the stage of experimental samples.

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The aim of this paper is the development of compact ytterbium lasers pumped by commercially available fibre-coupled diode sources for mobile laser systems that are in demand in high-precision spectroscopy, metrology and navigation, including satellite navigation systems.

2. Experimental setup

As the gain material we used a 1-mm-thick 7-wt. % Yb-doped KYW crystal cut so that the *c* axis lies along the emission direction ($E \| a, b$). The pump source was a fibre-coupled LIMO25-F100-DL980 diode laser with a pump wavelength of 980 nm, spectral FWHM bandwidth of less than 5 nm and maximum output power of 25 W; the fibre core diameter was 105 µm. Because the generation threshold and power are temperature dependent in ytterbium lasers, the crystal was cooled using a Peltier element to a temperature of 9 °C, at which sweating had not yet begun.

When use is made of typical resonator schemes (Fig. 1), due to asymmetric cooling a lens with strong astigmatism arises in the crystal, which significantly reduces the laser efficiency and does not allow one to obtain stable mode locking. Structurally, it is problematic to mount in such schemes a heatsink, which would be symmetrical relative to the axis of the incident radiation. For comparison with the characteristics of the laser schemes developed, we studied the characteristics of the laser shown in Fig. 1a. At a minimum possible length of the resonator, the intermode frequency was equal to 670 MHz. The measured minimum diameter of the pump spot on the active element was about twice larger than the diameter of the generated radiation. The dependence of the output power on the pump power is shown in Fig. 2 ($\eta_{\rm dif}$ = 17.4 %). For the femtosecond regime to be realised, we placed in the cavity a pair of prisms or GTI mirrors (Gires–Tournois interferometer mirrors) to compensate for the group velocity dispersion (GVD) and a SESAM, which led to an increase in the cavity length. Due to the influence of the astigmatic thermal lens in the crystal, the lasing threshold increased and the output power decreased several times (depending on the pump power). For this reason and because of incomplete compensation for the GVD, we failed to obtain the femtosecond regime.

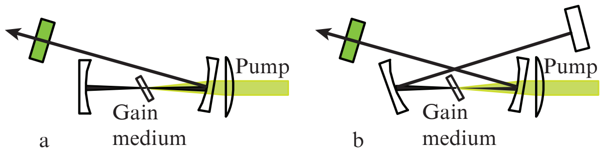

Figure 1. Typical configurations of femtosecond laser resonators.

To eliminate the thermal lens astigmatism we have proposed a scheme of an ytterbium laser with symmetrical cooling of the gain medium (Fig. 3). The Yb : KYW crystal (tapering of 0.5°) with a highly reflective dielectric coating was glued to a copper heatsink. The other crystal surface had an antireflection coating. In this configuration, the thermal lens is symmetrical with respect to the axis of generation and may be compensated by changing the distance between the spherical mirror and the crystal. In fact, this is a modified disc laser, characterised in that the thickness of the crystal is much larger than the diameter of the pump and output beam waists, which were 110 and 40 µm, respectively. For this reason, their axes should coincide. Polarisation of the pump and output radiation was directed parallel to the crystal axis (p-polarisation). To compensate for the GVD we used a pair of GTI mirrors (Layertec) with dispersion $D = -900 \pm 100$ fs^2.

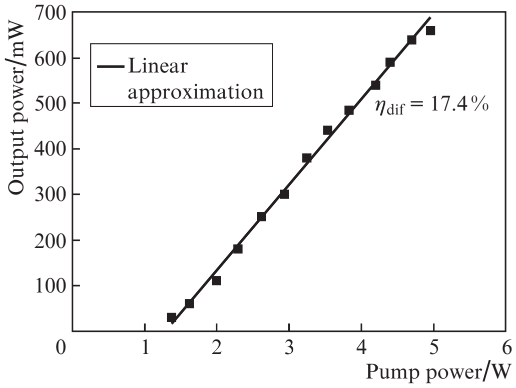

Figure 2. Dependence of the cw output power on the pump power for the laser configuration shown in Fig. 1a.

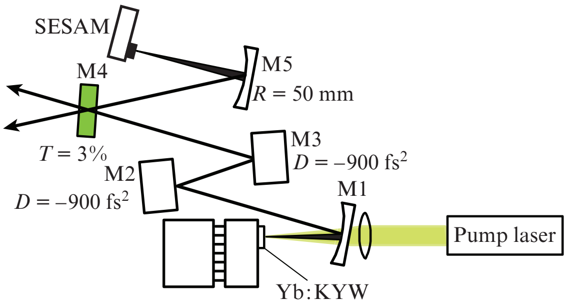

Figure 3. Scheme of a femtosecond ytterbium laser: (M1) dichroic mirror with a radius of curvature R = 50 mm; (M2) and (M3) GTI mirrors with a dispersion $D = -900 \pm 100$ fs^2 each; (M4) output mirror with a transmittance T = 3 %; (M5) spherical mirror with R = 50 mm. Pump radiation and output radiation are p-polarised.

To start the mode locking we used a SESAM (BATOP GmbH) with the following characteristics: saturable absorption A_0 = 1 % at a wavelength of 1040 nm, modulation depth of 0.6 %, saturation energy density of 120 µJ cm^{-2} and relaxation time constant of 500 fs. The intermode frequency was about 400 MHz. The output power as a function of the pump power for the free generation regime is shown in Fig. 4. The saturation of the dependence was not observed up to the pump power of at least 14 W. We obtained the maximum output power of 3.0 W at 9.5 W of pump power. The lasing threshold was 0.8 W and $\eta_{\rm dif}$ = 35 %. We failed to obtain mode locking, apparently due to incomplete compensation for the GVD. The disadvantage of this scheme lies in the fact that the focusing of multimode pump radiation is not optimal.

In the scheme shown in Fig. 5, the above disadvantage is minimised. Here, the focal length of the lens can be reduced; therefore, the pump radiation will be focused to a spot smaller in size and the efficiency of the laser will be increased. Furthermore, it is possible to optimise the ratio of the focal length of the lens and the radius of curvature of the spherical mirror. However, it is technologically challenging to fabricate

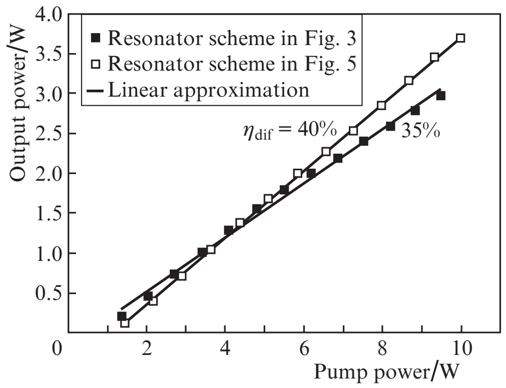

Figure 4. CW output power of the ytterbium laser with the resonator schemes given in Figs 3 and 5 as a function of pump power.

a deflection mirror (inclination angle of 45°) with large transmission and reflection for pump and output radiation having the same polarisation, respectively. Therefore, we used a mirror with a transmission of ~80% and less than 0.05% for the pump radiation polarised along the *a* axis of the crystal (p-polarisation) and for the output radiation polarised along the *b* axis (s-polarisation), respectively. The lasing threshold was 1 W and $\eta_{\text{dif}} = 40\%$ (Fig. 4). At a pump power of 14 W the maximum output power reached 4.9 W, i.e., η_{opt} = 35%, which is record high in the case of a multimode pump source. The pulse duration in the mode-locking regime was not measured; the intermode frequency was approximately 340 MHz, the output power in the mode-locking regime was 1.3 W at a pump power of 7W, the radiation wavelength was 1041 nm and the spectral FWHM bandwidth was about 2 nm. Mode-locking was not self-starting, i.e., when lasing was switched on or quenched, this regime could be launched by moving an element of the resonator. In mode-locked operation there appeared a narrow intermode frequency comb with a high (greater than 60 dB) signal-to-noise ratio. The mode-locking spectrum at the intermode frequency is shown in Fig. 6. When use is made of one GTI mirror ($D = -900$ fs^2), mode locking does not occur. When three mirrors (–2700 fs^2) are used, mode locking occurs; however, it is hard to start and is not stable, i.e., the point of complete compensation of dispersion lies between $D = -1800$ and -2700 fs^2. For complete compensation of the GVD, it is needed to select GTI mirrors with the desired characteristics or use a pair of wedges to fine-tune the intracavity dispersion.

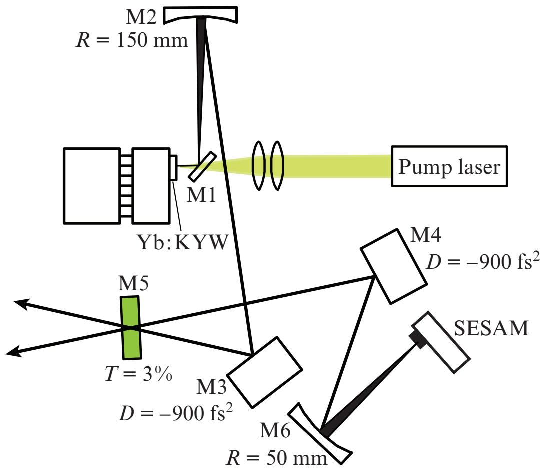

Figure 5. Scheme of a femtosecond ytterbium laser: (M1) dichroic mirror; (M2) dichroic mirror with R = 150 mm; (M3) and (M4) GTI mirrors with D = –900 ± 100 fs^2 each; (M5) output mirror with T = 3%; (M6) spherical mirror with R = 50 mm. Pump radiation is p-polarised and output radiation is s-polarised.

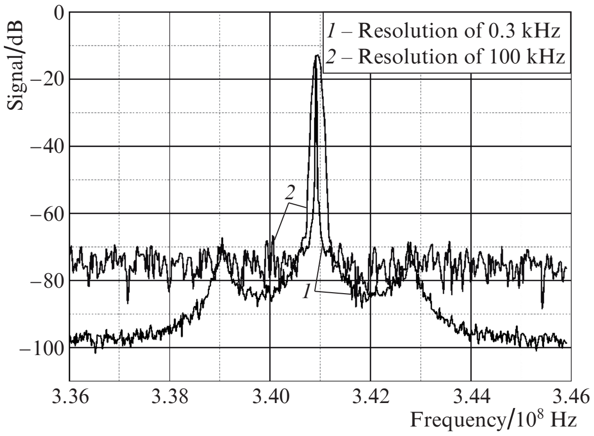

Figure 6. Emission spectra at the intermode frequency in the case of mode-locked operation, measured at a resolution of 0.3 and 100 kHz.

Currently, serial single multimode diode lasers are available with an output power up to 10 W, which are suitable for pumping the laser developed. Their use may facilitate the creation of a compact monoblock: laser + pump source. In addition, the scheme does not require special protection of the pump source from backscattered radiation because of its smallness compared with that of typical schemes [20–22], which is essential for mobile systems. Thus, the proposed scheme (Fig. 5) is promising for the development of compact laser systems, such as mobile precision femtosecond optical clocks. It should be noted that this scheme is not optimised for the maximum efficiency. The pump source used in this work has a circular polarisation of the output radiation. At the same time, the s-polarised pump radiation is used inefficiently due to lower absorption in the crystal ($E\|b$) and low bandwidth of the mirror, which reduces the overall efficiency and increases the lasing threshold. Figure 7 shows the dependences of the output power on the pump power at different polarisations of the pump radiation. In the case of the effective p-polarised pump radiation ($E\|a$), the lasing threshold decreased to 0.74 W, and η_{dif} increased to 46.4%. The limiting efficiency can be obtained when single-mode diode pumping is used, which allows the pump and output beam waists to be completely overlapped.

Thus, we have developed a promising scheme of a multimode-diode-pumped ytterbium laser. For a cw Yb:KYW laser we obtained record values of the differential (40%) and total optical (35%) efficiencies. Mode-locking was realised, which allows one to use the scheme for the development of compact laser systems, such as mobile femtosecond precision synthesisers. Optimisation of the laser parameters will increase its efficiency.

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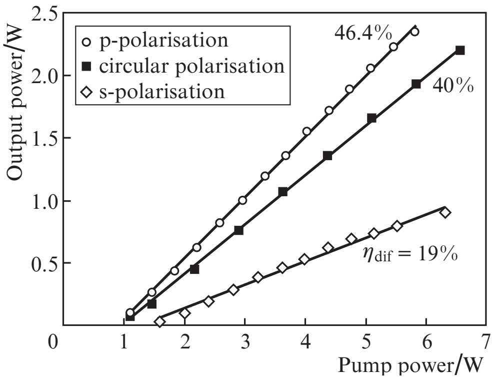

Figure 7. Dependences of the cw output power on the pump power in the case of circularly polarised, s-polarised (threshold of 1.2 W) and p-polarised (threshold of 0.74 W) pump radiation.

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