Highly efficient multimode diode-pumped Yb:KYW laser

S A Kuznetsov1, V S Pivtsov1, 2, A V Semenko1, 2 and S N Bagayev 1, 3

1 Institute of Laser Physics SB RAS, 13/3 Acad. Lavrentyev ave., Novosibirsk 630090, Russia
2 Novosibirsk State Technical University, 20 K. Marx ave., Novosibirsk 630073, Russia
3 Novosibirsk State University, 2 Pirogova str., Novosibirsk 630090, Russian Federation

E-mail: clock@laser.nsc.ru

Abstract. Record high differential efficiency (53.2%) and full optical efficiency (48%) for a multimode diode-pumped Yb:KYW laser have been achieved. The characteristics of the laser and methods for improving its efficiency using a distributed Bragg reflector tapered diode laser (DBR TDL) are discussed.

1. Introduction
Optical frequency synthesizers based on femtosecond lasers are most important blocks of precision laser systems for measurement of absolute optical frequencies and their stability [1–3]. They are also used to solve the problem of transferring the frequency characteristics of optical frequency standards to the radio frequency range. As most of the master lasers are used femtosecond Ti:S laser or Er fiber lasers [4–6]. But in recent years, synthesizers on the basis of ytterbium-doped crystals are becoming more popular [7–10]. The absorption bands of ytterbium crystals coincide with the generation range of high-power semiconductor diode lasers (940 nm and 980 nm). Among ytterbium-doped media, the potassium tungstates Yb:KYW and Yb:KGW are most promising owing to large absorption cross-sections and induced radiation, wide luminescence band, and rather high heat conduction. In this paper, various schemes of small cavities of a Yb:KYW laser with high-power multimode diode pumping are investigated.

2. Experimental setup and results
As an active medium, we used Yb:KYW crystal with 5 at. % Yb3+ ions and a thickness of 1.5 mm. The crystals were cut in the direction of axis c (E || a, b). The temperature of the crystal was stabilized at 9°C using a Peltier element. The source of pumping was a LIMO25-F100-DL980 laser with a multimode fiber output. The central radiation wavelength was 981 nm, the maximum output power was 25 W, and the fiber core diameter was 105 µm. The pump laser radiation had circular polarization.

To eliminate the thermal lens astigmatism we have proposed a scheme of an ytterbium laser with symmetrical cooling of the gain medium (figure 1). 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 mm, 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 \( D = -900 \pm 100 \text{ fs}^2 \).

**Figure 1.** Scheme of a femtosecond ytterbium laser.

To start the mode locking we used a SESAM (BATOP GmbH). 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 figure 2. The saturation of the dependence was not observed up to a pump power of 14 W. We obtained a maximum output power of 3.0 W at 9.5 W of pump power. The lasing threshold was 0.8 W and \( \eta_{\text{dif}} = 35 \% \). 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.

**Figure 2.** CW output power of the ytterbium laser with the resonator schemes given in figures 1 and 3 as a function of pump power.

In the scheme shown in figure 2, 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. We used a mirror M1 with a transmission of \( \sim 80 \% \) 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.

![Figure 3. Scheme of a femtosecond ytterbium laser.](image)

Figure 3. Scheme of a femtosecond ytterbium laser.

![Figure 4. Emission spectra at the intermode frequency in the case of mode-locked operation, measured at a resolution of 0.3 and 100 kHz.](image)

Figure 4. Emission spectra at the intermode frequency in the case of mode-locked operation, measured at a resolution of 0.3 and 100 kHz.

The lasing threshold was 1 W and $\eta_{\text{diff}} = 40\%$ (figure 2). At a pump power of 14 W the maximum output power reached 4.9 W, i.e., $\eta_{\text{diff}} = 35\%$, 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 7 W, the radiation wavelength was 1041 nm and the spectral FWHM bandwidth was about 2 nm. 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 figure 4.

![Figure 5. CW output power of the ytterbium laser for different output couplers.](image)

Figure 5. CW output power of the ytterbium laser for different output couplers.

Measurements for output mirrors with various transmission coefficients (1%, 2.2%, 3%) have been made (figure 5). The differential efficiency was 53.2%, the optical efficiency was 48%, and the
maximal output power was 3.94 W at a pump power of 8.2 W. This is a record result when using a multimode pump source.

Maximum efficiency can be achieved by using single-mode diode pumping for this scheme when the pump and generation waists fully overlap. The pump source is a distributed Bragg reflector tapered diode laser [11]. The pump diode consists of a 4-mm-long gain-guided tapered section and a 2-mm-long 4-μm-wide index-guided standard ridge-waveguide section containing a 1-mm-long surface Bragg grating. The DBR TDL emits at 981 nm with a spectral linewidth of less than 20 pm (FWHM). In addition, the device has a nearly diffraction limited output beam with a lateral beam propagation factor \( M^2_{1/e^2} = 1.3 \) containing more than 72% of the power in the central lobe. The maximum output power is 7 W.

3. Conclusion
A promising small ytterbium laser with a diode pumping laser was designed. Record high efficiencies (a differential efficiency of 53.2% and a total optical efficiency of 48%) were obtained for a laser with an Yb:KYW crystal in the continuous-wave regime. Mode-locking laser operation with a pulse rate of ~340 MHz was demonstrated. This allows us to use the proposed design in the construction of small laser systems (e.g., mobile precision femtosecond synthesizers). The ultimate efficiency of the proposed laser could be achieved with single-mode diode pumping lasers and by optimizing the focusing system.

Acknowledgments
This work was partially supported by the Russian Foundation for Basic Research (project no. 16-02-00639-a) and Russian Presidential Grant (NSh-6689.2016.2).

References
[1] Bagayev S N, Chepurov S V, Klementyev V M et al. 2000 Appl. Phys. B 70 375
[2] Udem Th, Holzwarth R and Hansch T W 2002 Nature 416 233
[3] Bagayev S N, Denisov V I, Klementyev V M et al. 2004 Laser Phys. 14 1
[4] Pivtsov V S, Nyushkov B N, Korel I I et al. 2014 Quantum Electronics 44 507
[5] Zimmermann M, Gohle C, Holzwarth R et al. 2004 Optics Lett. 29 310
[6] Korel I I, Nyushkov B N, Denisov V I et al. 2014 Laser Physics 24 074012
[7] Pekarek S, Sudmeyer T, Lecomte S et al. 2011 Opt. Express 19 16491
[8] Endo M, Ozawa A and Kobayashi Y 2012 Opt. Express 20 12191
[9] Kuznetsov S A and Pivtsov V S 2014 Quantum Electronics 44 444
[10] Kirpichnikova A A, Kuznetsov S A and Pivtsov V S 2015 Bulletin of the Russian Academy of Sciences. Physics 79 169
[11] Fiebig C, Blume G, Uebernickel M et al. 2009 IEEE J. of Selected Topics in Quantum Electronics 15 978