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A.S. GRABTCHIKOV[1,✉]
A.N. KUZMIN[1]
V.A. LISINETSKII[1]
V.A. ORLOVICH[1]
A.A. DEMIDOVICH[2]
M.B. DANAILOV[3]
H.J. EICHLER[4]
A. BEDNARKIEWICZ[5]
W. STREK[5]
A.N. TITOV[6]

Laser operation and Raman self-frequency conversion in Yb:KYW microchip laser

[1] B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, F. Skaryna Ave. 68, 220 072, Minsk, Belarus
[2] Institute of Molecular and Atomic Physics, National Academy of Sciences of Belarus, F. Skaryna Ave. 70, 220 072, Minsk, Belarus
[3] Laboratory for Lasers and Optical Fibres, Sincrotrone-Trieste SS14, km. 163.5, Trieste, Italy
[4] TU Berlin – Optisches Institut, Str. d. 17. Juni 135, 10 623 Berlin, Germany
[5] Institute for Low Temperature and Structure Research, Polish Academy of Sciences, 50-950 Wroclaw 2, PO Box 937, Poland
[6] Vavilov State Optical Institute, Byrzhevaya line 12, 199 034 St.-Petersburg, Russia

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ABSTRACT We present a diode-pumped Yb:KYW microchip laser. The passive Q-switched and CW regimes of operation for the Yb:KYW microchip laser have been investigated. An efficiency for CW operation of up to 10% with regard to incident pump has been obtained. Raman self-frequency conversion in the Q-switched regime has been observed.

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1 Introduction

Potassium yttrium and potassium gadolinium tungstates are known as good hosts for efficient neodymium- and ytterbium-doped laser media which are used in miniature diode-pumped solid-state lasers, including Raman lasers with self-frequency conversion [1–7]. Because microchip lasers are extremely compact, simple to fabricate, and robust, they have found many applications in laser systems as CW and passive Q-switched coherent sources. The passive Q-switched regime for operation of microchips is of special interest due to their capability of producing nano- and sub-nanosecond light pulses of high peak power for the subsequent nonlinear frequency conversion.

The plano/plano configuration of a microchip resonator, which is on the limit of cavity stability, requires careful choice of a gain medium for a chip-set in order to obtain efficient operation [8]. Due to the high efficiency of laser operation provided by the use of Nd^{3+}- and Yb^{3+}-doped double tungstates, the latter could be used as active materials for microchip application. It was experimentally shown for example that Nd^{3+}:$KGd(WO_4)_2$ is a laser material which is suitable for a microchip laser [2, 9]. Most previous work on microchip lasers emitting at a fundamental wavelength of $\sim 1\,\mu m$ has been performed with neodymium-doped materials as a gain medium, and to our knowledge there is only one paper on experimental research of a ytterbium-doped laser crystal where the passive Q-switched Yb:YAG microchip performance with the plano/plano cavity configuration was described [10]. At the same time, ytterbium-doped materials are a good choice for a new type of solid-state lasers – radiation-balanced lasers – and can be used for optical cooling and other new applications [11].

In this work, a diode-pumped Yb^{3+}:$KY(WO_4)_2$ microchip laser with a plano/plano resonator was experimentally investigated. Both CW and passive Q-switched regimes of operation were realized and studied. During Q-switching experiments, stimulated Raman scattering with self-frequency conversion was achieved.

The main features of the Yb:KYW laser medium are the broad absorption band centered at 981 nm, where powerful commercial laser diodes are available, relatively large absorption coefficient ($17\,cm^{-1}$ for the typical 5 at% Yb^{3+} concentration that corresponds to an ion concentration of $3.2\times10^{20}\,cm^{-3}$), and relatively inexpensive, reproducible, and easy growth technology allowing production of crystals with a high optical quality. Double tungstates are also highly efficient Raman media due to the structure symmetry related to the vibration symmetry of a molecular WO_4-group: for Yb:KYW pumped at $\lambda = 1064$ nm the Raman gain coefficient is 5.1 cm/GW [12] for a Raman shift of $905\,cm^{-1}$. This property considerably extends their application range in laser systems. Doped with different rare-earth-element ions, double tungstates could be a good choice as active media for lasers with self-frequency conversion.

2 Experiment

The Yb:KYW microchip laser used in the experiment (Fig. 1) was made from 10 at% Yb^{3+}-doped material which was cut along the *b* axis and polished to be 1.1-mm long. One polished surface (input mirror) was coated to be highly reflective in the 1020–1150-nm wavelength range and with a 80% transmittance at the pump wavelength. The other polished surface was antireflection-coated for the fundamental and first Stokes wavelengths.

✉ Fax: +375-17/2840-879, E-mail: asg@dragon.bas-net.by

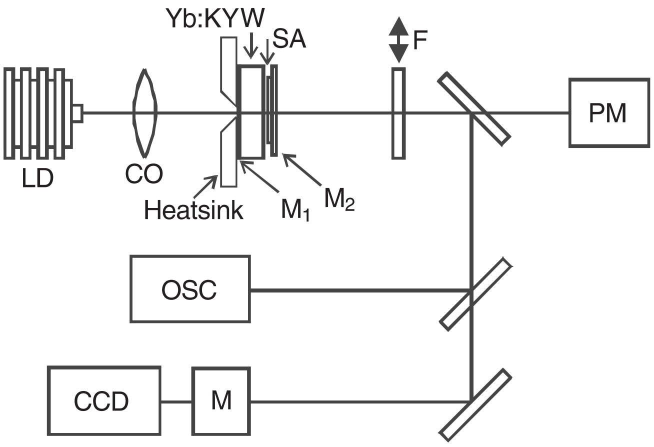

FIGURE 1 Experimental setup. LD – laser diode, CO – coupling optics, M_1 and M_2 – cavity mirrors, SA – saturable absorber, F – spectral filters, CCD – CCD array, M – monochromator, PM – power meter, OSC – oscilloscope

The active element was mounted on a copper heat sink to promote symmetrical heat removal. The output coupler was flat mirrors with 90%, 95%, 98%, and high (HR) reflections at the 1030-nm wavelength. The last two mirrors provided a transmittance of about 2% at 1130 nm (the first Stokes wavelength). An antireflection-coated ∼ 100-μm-thick Cr^{4+}:YAG plate with an initial transmission of 97% was used as a passive Q-switch, which was mounted directly on the output coupler. The pump source was a multimode diode laser providing 1 W at 980 nm from a 100 × 1-μm emitting area. The light from the diode laser was delivered to the active element by the focusing system consisting of a triplet collimator ($NA = 0.5$), a 4^x cylindrical telescope, and a focusing lens ($f = 10$ mm). This system provided about 70% of transmission at the 980-nm wavelength and the pump spot size was about 80-μm diameter.

3 Results

The output characteristics obtained for the CW regime of operation are shown in Fig. 2. The curve presented in Fig. 2a shows the optimal output characteristics obtained in experiments for a microchip laser with an output-coupler reflectivity of 90%. Maximum CW output power achieved in our experiments was 54 mW at ∼ 550 mW of the incident pump power. The slope and optical efficiency were 23% and 10%, respectively. For quasi-three-level systems like Yb-doped media it is difficult to estimate experimentally the part of the absorbed pump power because of the re-absorption and saturation effects inherent in such systems. Therefore to evaluate the laser efficiency we used the incident pump power, although the use of this parameter for the absorbed pump power underestimates the real laser efficiency.

As is seen in Fig. 2b, the spectra of the microchip emission exhibit a mode structure, which most likely is formed due to the coupling of two Fabry–Perot etalons. One etalon is formed by a parallel sided active element. The other is an air gap between the active element and the output coupler, which was in our experiments about 100 μm.

For the passive Q-switched regime of operation the best result was obtained with the output coupler having $R_{oc} = 0.95$ (Fig. 3a). For the maximum pump power, the output average power was as high as 26 mW (repetition rate about 49 kHz) with the optical efficiency about 5%. The lasing spectra for the Q-switched regime of operation demonstrate almost the same mode structure (see Fig. 3b), differing from the CW spectra by the spacing between the mode groups. The Cr:YAG parallel-

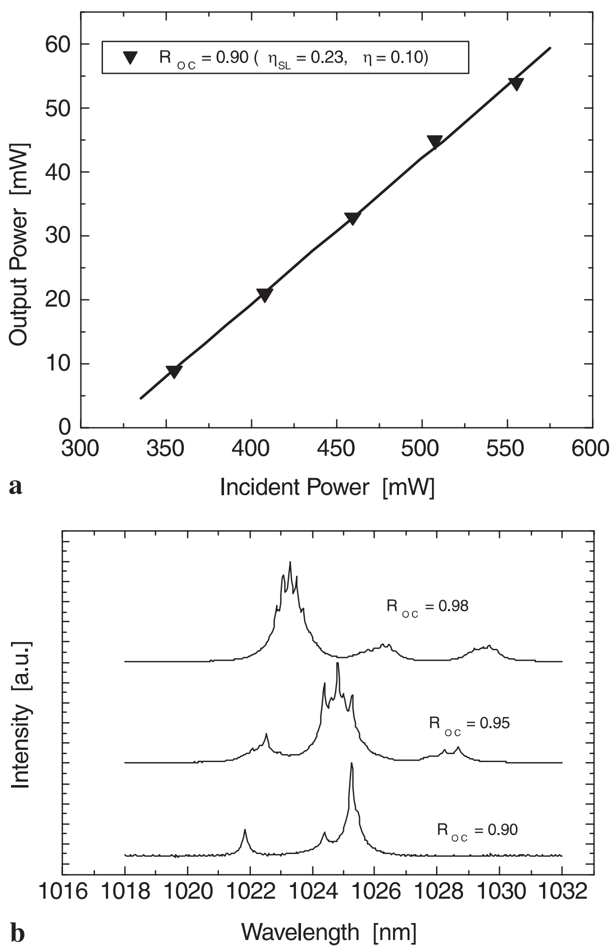

FIGURE 2 Output characteristics of CW Yb:KYW microchip laser: **a** input–output power curve, **b** emission spectra

sided 100-μm-thick plate plays a role of a third Fabry–Perot etalon within a cavity.

The detailed investigation of temporal characteristics for the passive Q-switched regime of operation revealed complicated dynamics. Depending on the cavity alignment, we observed simultaneous operation at two cavity modes with different intensities, causing high jitter and unstable output power. Most probably this behavior is due to the following reasons. The first is the Raman self-frequency conversion process, which depletes the stronger mode and therefore promotes the build-up of the other mode. The second is the thermal lens of the active element, which may be negative in one plane as it is in Nd:KGW [2] and can also significantly influence the resonator stability.

For the maximum pump power and an output mirror reflectance of 0.95, the repetition rate was about 49 kHz. The oscilloscope used in our experiments did not allow us to measure pulses shorter than 2 ns (half-width) although, in our estimation, the half-width of the pulse duration emitted by the microchip should be less than 1 ns. Even assuming the pulse half-width to be 2 ns, the peak power obtained from the microchip was about 265 W.

The first Stokes generation of stimulated Raman scattering in KYW with a shift of about 905 cm^{-1} was observed for the HR and $R = 0.98$ output couplers (see Fig. 3b). Frequency conversion was estimated to take place for the strongest spectral group of the fundamental emission. However, if two groups of spectral modes with approximately equal intensities are observed in the fundamental spectrum, the Raman spectrum exhibits two lines as well. The best result for Raman self-frequency conversion in our microchip was achieved for the $R = 0.98$ output coupler, where at the maximum pump power we obtained 2 mW of the average Stokes power.

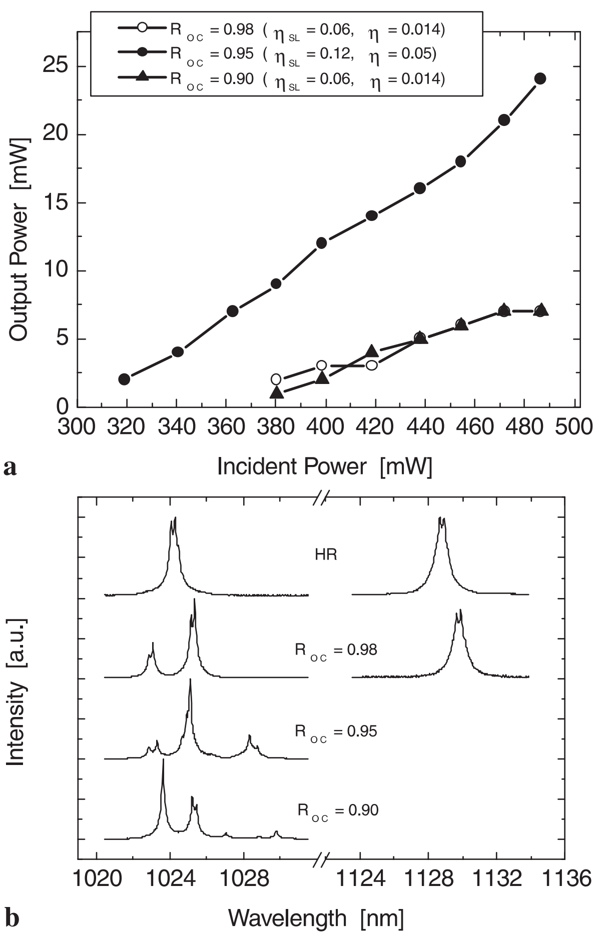

FIGURE 3 Output characteristics of a passive Q-switched Yb:KYW microchip laser: **a** input–output power curves, **b** emission spectra

Ways to improve the power, spectral, and temporal characteristics of a Yb:KYW microchip laser could be the following: employment of a monolithic cavity for CW microchips, minimization of the spacing between the intracavity elements, use of high-quality antireflection coatings for intracavity surfaces, and application of a special athermic cut along the proper direction of the active elements that can provide the formation of an isotropic positive thermal lens. These improvements and optimization of the output-coupler reflectivity at the first Stokes wavelength can also increase the efficiency of Raman self-frequency conversion.

4 Summary

In conclusion, we present for the first time to our knowledge a diode-pumped Yb:KYW microchip laser operating both in CW and in passive Q-switched regimes. Also, we demonstrated the operation of a diode-pumped Raman microchip laser with self-frequency conversion.

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