

V.E. KISEL^{1,✉}
A.E. TROSHIN¹
N.A. TOLSTIK¹
V.G. SHCHERBITSKY¹
N.V. KULESHOV¹
V.N. MATROSOV²
T.A. MATROSOVA²
M.I. KUPCHENKO²

Q-switched Yb³⁺:YVO₄ laser with Raman self-conversion

¹International Laser Center, 65 F. Scoriny Ave., Build. 17, Minsk, Belarus
²Solix Ltd., 77 Partizanski Ave., Minsk, Belarus

Received: 29 October 2004 / Revised version: date
Published online: date • © Springer-Verlag 2004

ABSTRACT We report the efficient continuous-wave (CW) and Q-switched laser operation of a diode-pumped Yb:YVO₄ laser. A CW output power of 1 W with a slope efficiency of 59% with respect to absorbed pump power was demonstrated. Passively Q-switched with a Cr⁴⁺:YAG saturable absorber, a Yb:YVO₄ laser with Raman conversion was demonstrated. Q-switched 18.7-μJ pulses with a pulse duration of 17 ns and a peak power up to 1 kW were obtained at 1018-nm fundamental wavelength and 3.6-μJ pulses with a pulse duration of 6 ns and a peak power of about 0.6 kW were obtained at 1119.5-nm first-Stokes wavelength.

PACS 42.55.Xi; 42.60.Gd; 42.70.Hj

1 Introduction

Crystals doped with trivalent ytterbium ions (Yb³⁺) are of great interest for directly diode-pumped high-power lasers in the spectral range near 1 μm [1]. Recently, continuous-wave (CW) laser operation of Yb:YVO₄ was demonstrated independently by two groups [2–4]. Yb-doped YVO₄ was shown to be a promising material for thin-disk laser and femtosecond pulse generation due to the strong and comparatively broad absorption band near 985 nm, the extremely low quantum defect of about 3.5%, and the broad gain bandwidth of about 30 nm. Moreover, YVO₄ crystal is a promising Raman medium [5]. The Raman gain coefficient (~4.5 cm/GW) and dephasing time (~3.5 ps) for the 892-cm⁻¹ mode are close to those of double tungstate crystals [6], which are used successfully for Raman conversion of nano- and picosecond pulses including a self-Raman conversion [7, 8]. Demidovich et al. have presented Raman self-conversion in a diode-pumped Nd:YVO₄ microchip laser [9]. With Cr⁴⁺:YAG crystal as saturable absorber, they reached a conversion efficiency to the Stokes power of 3% for absorbed pump laser diode power. The pulse duration obtained at the Raman wavelength (1.18 μm) was as short as 830 ps. In this letter we present for the first time to our knowledge the self-stimulated Raman scattering in a passively Q-switched diode-pumped Yb:YVO₄ laser.

2 Laser experiments

The CW laser experiments were carried out with a nearly hemispherical laser cavity. It consisted of a 50-mm radius-of-curvature output coupler (OC) and a plane mirror highly reflecting at 1020–1100 nm. The Yb:YVO₄ single crystals were grown by Solix Ltd. by using the Czochralski technique. Yb:YVO₄ crystal was cut along the *a* axis for the possible operation in both π - and σ -polarizations ($E//c$ and $E\perp c$). The Yb concentration in YVO₄ crystal used for laser experiments was 3.1 at.%. The laser element with a thickness of 1.76 mm was antireflection coated at the pump and laser wavelengths and mounted onto an aluminium heat sink kept at 10°C. A CW fiber-coupled ($\varnothing = 100 \mu\text{m}$, N.A. = 0.22) laser diode with a maximum output power of about 8 W at 980 nm was used for longitudinal pumping of the active element through a plane mirror. This mirror has only 63% transmission at the pump wavelength, reducing the maximum incident pump power at the crystal to 5 W. The pump beam was focused into the 110-μm spot with a confocal parameter of about 2.5 mm inside the laser crystal. The cavity-mode diameter for the TEM₀₀ transversal mode at the active element was close to the pump-beam waist.

Input–output diagrams for the Yb:YVO₄ laser in continuous-wave regime with output-coupler transmittances of 1, 3.5, and 5.5% are presented in Fig. 1. A maximum output power of 0.98 W at 1023 nm for the TEM₀₀ mode with a slope efficiency of 59% with respect to the absorbed pump power was obtained with the 3.5% OC. For Yb:YVO₄ lasers with output-coupler transmittances of 1 and 5.5% the slope efficiencies decreased, respectively, to 31 and 47% with an output power of 0.56 W at 1033 nm and of 0.74 W at 1020 nm. In all cases the laser output was π -polarized, where the stimulated emission cross section is higher than for σ -polarization. Laser thresholds for the 1, 3.5, and 5.5% output couplers were estimated to be 383, 458, and 573 mW of the absorbed pump power, respectively.

For Q-switching experiments we used the cavity configuration described above. As a passive shutter an antireflection-coated 120-μm Cr⁴⁺:YAG crystal was used with an initial transmittance of about 97% at 1020 nm. It was mounted onto the opposite side of the heat sink 4 mm apart from the active element. In Q-switched mode the laser produced up to 555 and 583 mW of total output power with slope efficiencies of 40 and 42% for 3.5 and 5.5% OCs, respectively. The Q-switch

✉ Fax: +375-17-2326286, E-mail: vekisel@ilc.by

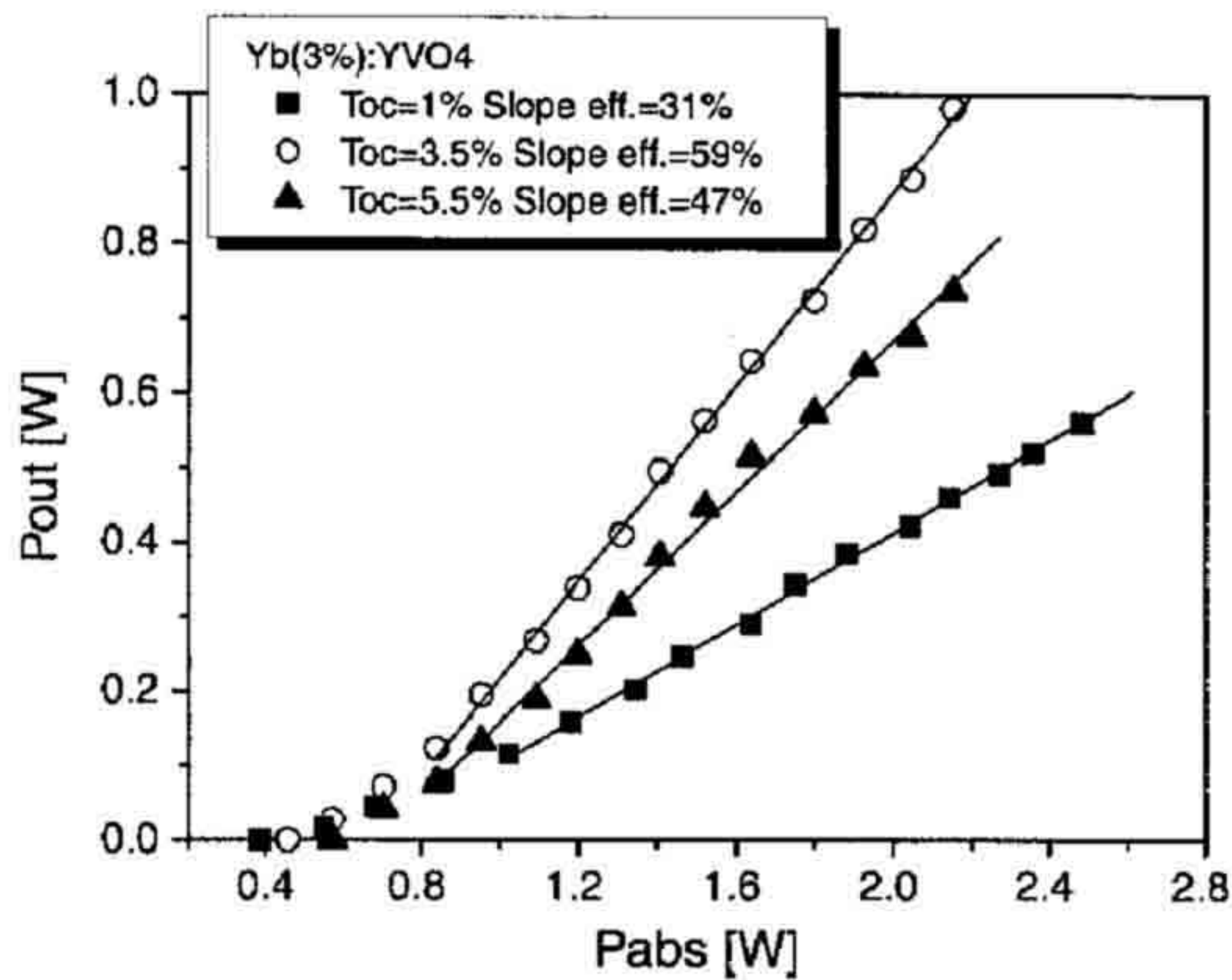


FIGURE 1 Output power versus absorbed pump power for CW Yb:YVO₄ laser

conversion efficiency (P_{Q-sw}/P_{CW}) was determined to be 57 and 79% for the corresponding OCs. Input-output diagrams for the Q-switched Yb:YVO₄ laser are shown in Fig. 2.

The Q-switched Yb:YVO₄ laser emitted at two wavelengths simultaneously owing to multipass intracavity Raman conversion of fundamental laser emission in the laser host crystal. The output radiation at fundamental and first-Stokes wavelengths was π -polarized. For this polarization SRS in YVO₄ is observed at 892-cm⁻¹ Raman frequency that has the highest cross section [6]. The output pulses with an energy of 16.4 μ J and a pulse duration of 17 ns at 1014-nm fundamental wavelength and with an energy of 1.1 μ J and a pulse duration as short as 8 ns at 1115-nm first-Stokes wavelength were obtained for an OC transmittance of 5.5% at the highest pump power. Maximum conversion efficiency to first-Stokes power of 4.2% for absorbed pump laser diode power was obtained with the 3.5% OC. In this case, the output pulses with an energy of 18.7 μ J and a pulse duration of 18 ns at 1018-nm fundamental wavelength and with an energy of 3.6 μ J and a pulse duration as short as

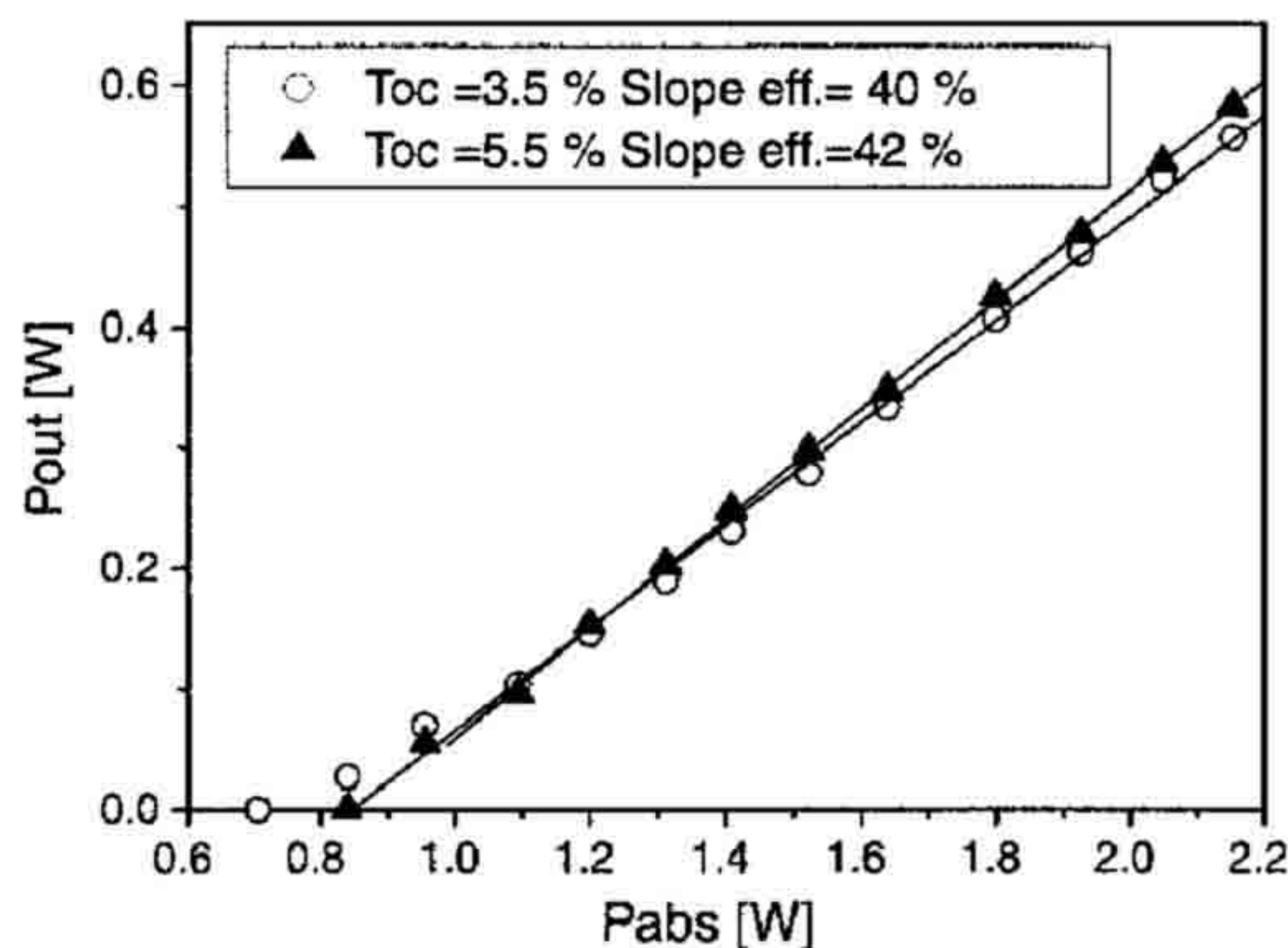


FIGURE 2 Average output power of Q-switched Yb:YVO₄ laser versus absorbed pump power for two different output couplers

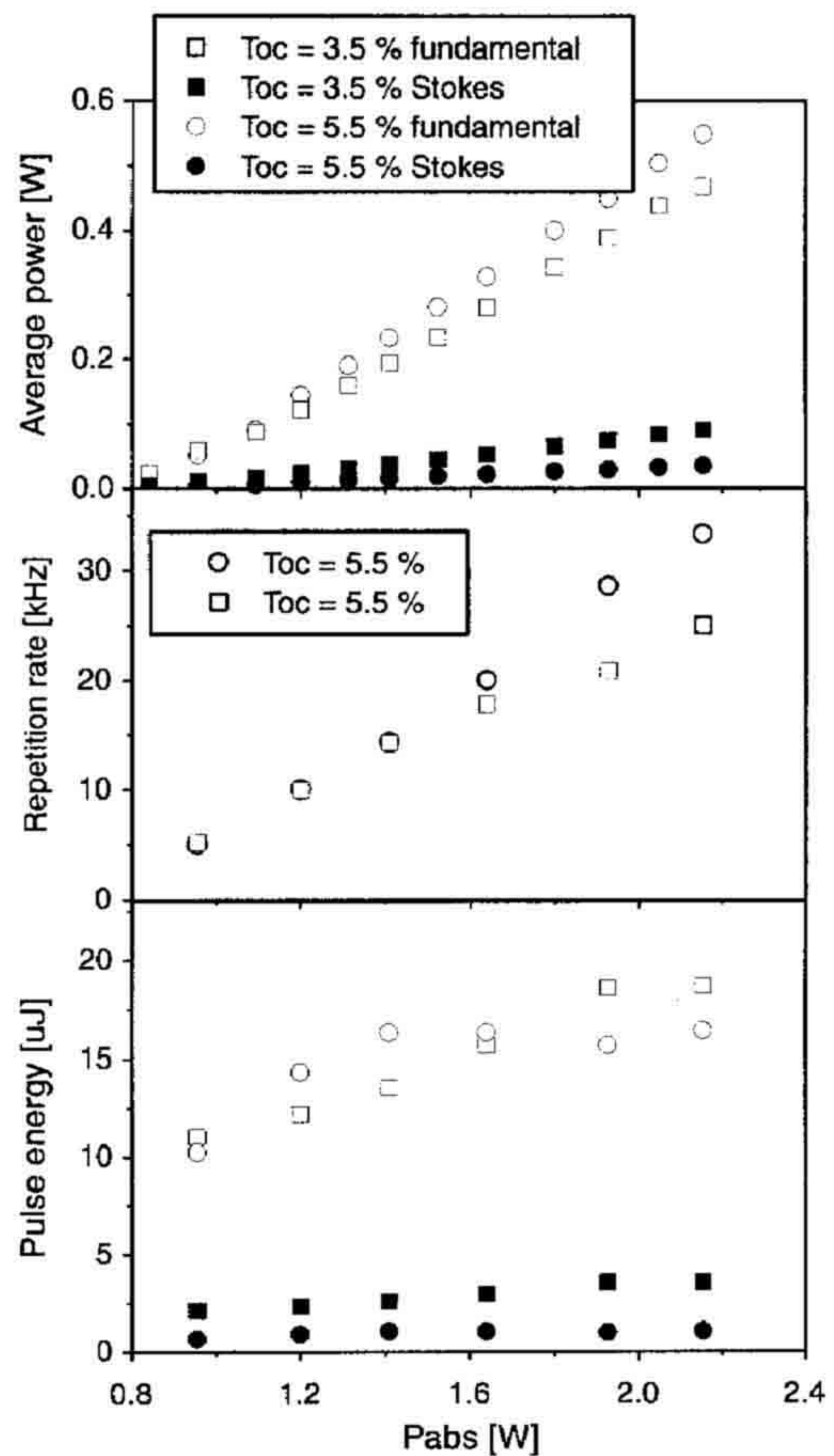


FIGURE 3 Average power, repetition rate, and pulse energy at fundamental and first-Stokes wavelengths of passively Q-switched Yb:YVO₄ laser versus absorbed pump power

6 ns at 1119.5-nm first-Stokes wavelength were obtained. The transmittance at Raman wavelengths for both OCs was about 12%. Higher pump-to-first-Stokes conversion efficiency with the 3.5% OC was associated with a higher level of the intracavity pulse intensity.

Figure 3 shows dependences of average power, repetition rate, and pulse energy at the fundamental and first-Stokes wavelengths on the absorbed pump power for two different OCs. The average output power and the repetition rate increase linearly with increasing of the absorbed pump power. As theory predicts [10], starting from a certain value of the pump power the pulse energy (see Fig. 3), pulse duration, and peak power (see Fig. 4) at the fundamental wavelength remain nearly constant. Pulse widths at the Raman wavelength remain constant in the whole range of pump power for both OCs.

Since the absorption cross section of the saturable absorber (5×10^{-18} cm²) is much higher than the cross section of the lasing transition of Yb ions in the YVO₄ crystal

Output coupler transmission (%)	Wavelength (nm)	Pulse width calc. (ns)	Pulse width measured (ns)	Repetition rate (Hz)	Average output power (mW)	Pulse energy (μ J)	Peak power (kW)
3.5	1018	20.2	18	25	468	18.7	1.04
	1119.5		6		89	3.6	0.59
5.5	1014	19.6	17	33.3	548	16.4	0.97
	1115		8		35	1.1	0.13

TABLE 1 The parameters of Q-switched diode-pumped Yb:YVO₄ laser with Cr:YAG saturable absorber

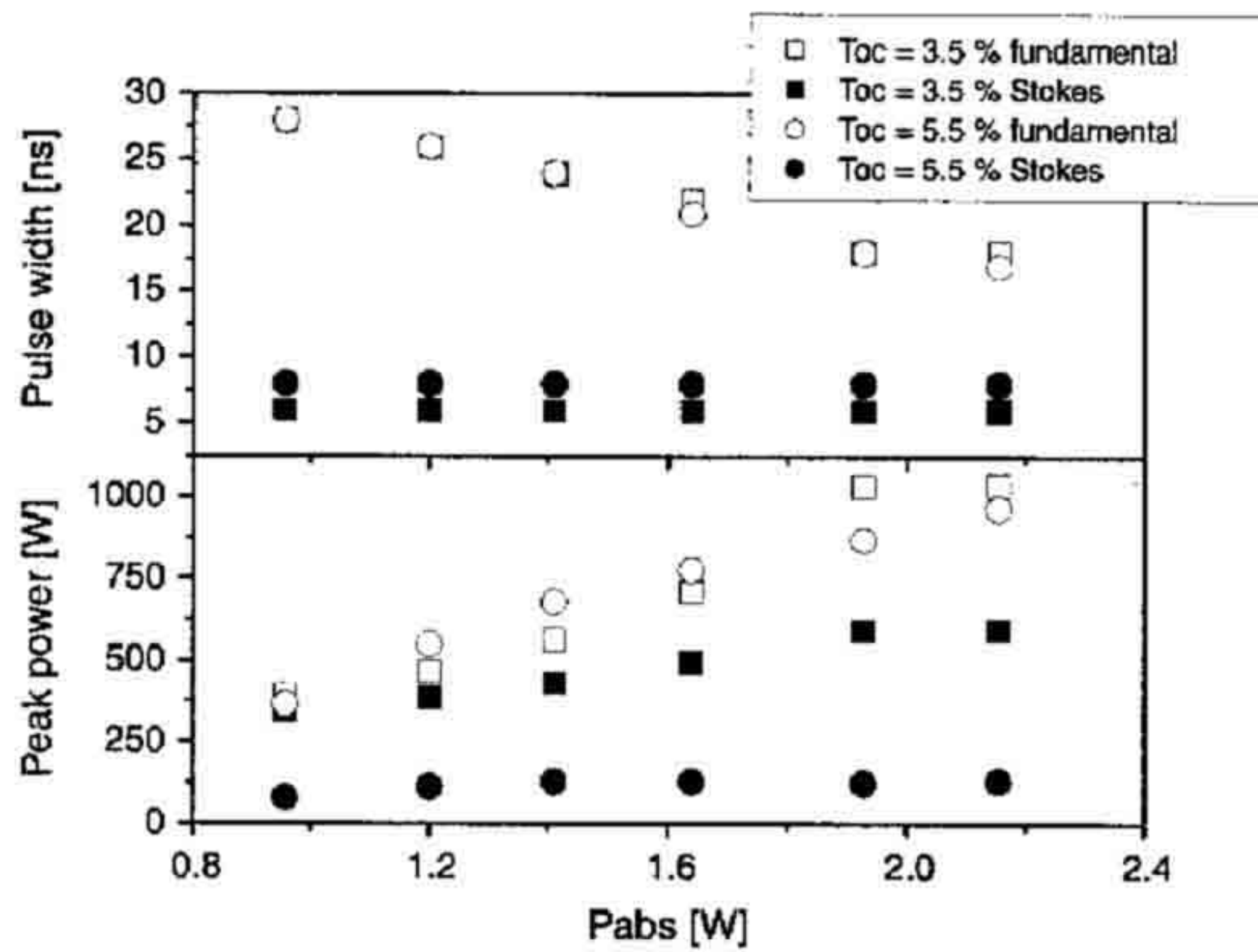


FIGURE 4 Pulse width and peak power at fundamental and first-Stokes wavelengths of passively Q-switched Yb:YVO₄ laser versus absorbed pump power

(1×10^{-20} cm²), the resulting pulse width is described by [10]

$$t_p = \frac{0.86t_{rt}}{\gamma_{sat,rt}} \left[\frac{\delta(1+\delta)\eta}{\delta - \ln(1+\delta)} \right], \quad (1)$$

where t_{rt} is the round-trip time of light within the laser cavity, η is the energy-excitation efficiency of the laser pulse, given by $\eta(1+\delta) = -\ln(1-\eta)$, and $\delta = \gamma_{sat,rt}/(\gamma_{par,rt} + \gamma_{op})$ is the ratio of saturable to unsaturable cavity losses, where $\gamma_{sat,rt}$ is the round-trip saturable-loss constant, $\gamma_{par,rt}$ is the round-trip unsaturable intracavity parasitic loss constant, and γ_{op} is the output-coupling loss constant. The round-trip saturable losses were determined to be 6%. The round-trip unsaturable intracavity parasitic losses were estimated to be 17.5 and 24% for OC transmittances of 3.5 and 5.5%, respectively. These values include mainly the reabsorption losses in the Yb:YVO₄ crystal at 1018- and 1014-nm laser wavelengths, respectively,

for 3.5 and 5.5% OCs. Calculated pulse widths at the fundamental wavelength of 20.2 and 19.6 ns for corresponding OCs are in good agreement with measured values. A summary of the laser experiment results is presented in Table 1.

3 Conclusion

In summary, CW operation of a Yb³⁺:YVO₄ laser at 1023 nm with about 1-W output power and a slope efficiency of 59% with respect to the absorbed pump power was demonstrated. Efficient Q-switched laser operation with a self-frequency Raman conversion was obtained by using a Cr⁴⁺:YAG passive shutter, and laser pulses of 18.7 and 3.6 μ J in energy with pulse durations of 18 and 6 ns and a repetition rate of 25 kHz were produced at 1018-nm fundamental and 1119.5-nm first-Stokes wavelengths, respectively.

REFERENCES

- 1 W.F. Krupke, IEEE J. Sel. Top. Quantum Electron. 6(6), 1287 (2000)
- 2 V.E. Kisel, A.E. Troshin, V.G. Shcherbitsky, N.V. Kuleshov, V.N. Matrosov, T.A. Matrosova, M.I. Kupchenko, F. Brunner, R. Paschotta, F. Morier-Genoud, U. Keller, in *EPS-QEOD Europhoton Conference*, Lausanne, 2004, Conference Digest, PD2
- 3 C. Krankel, D. Fagundes-Peters, S.T. Fredrich, J. Johannsen, M. Mond, Q2 G. Huber, M. Bernhagen, R. Uecker, Appl. Phys. B 79(5), 543
- 4 V.E. Kisel, A.E. Troshin, V.G. Shcherbitsky, N.V. Kuleshov, V.N. Q3 Matrosov, T.A. Matrosova, M.I. Kupchenko, Opt. Lett. (accepted)
- 5 A.A. Kaminskii, K. Ueda, H.J. Eichler, Y. Kuwano, H. Kouta, S.N. Bagaev, Th.H. Chyba, J.C. Barnes, M.A. Gad, T. Murai, J. Lu, Opt. Commun. 194, 201 (2001)
- 6 P. Cerny, P.G. Zverev, H. Jelinkova, T.T. Basiev, Opt. Commun. 177, 397 (2000)
- 7 A.S. Grabchikov, A.N. Kuzmin, V.A. Lisinetskii, G.I. Ryabtsev, V.A. Q4 Orlovich, A.A. Demidovich, J. Alloys Compd. 300-301, 300 (2000)
- 8 V.E. Kisel, V.G. Shcherbitsky, N.V. Kuleshov, in *Advanced Solid-State Photonics (Trends Opt. Photon. 83)*, ed. by J. Zayhovski et al. (Optical Society of America, Washington, DC, 2003), p. 189 Q5
- 9 A.A. Demidovich, L.E. Batay, A.S. Grabchikov, V.A. Lisinetskii, V.A. Orlovich, A.N. Kuzmin, in *ASSP 2004*, Technical Digest, TuB9
- 10 J.J. Zayhovski, P.L. Kelley, IEEE J. Quantum Electron. 27, 2220 (1991)