Resonantly pumped Q-switched Er:GdVO$_4$ laser

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We describe a Q-switched Er:GdVO$_4$ laser resonantly pumped by a MgO-doped periodically poled LiNbO$_3$ optical parametric oscillator (MgO: PPLN OPO) at 1 536 nm. In continuous-wave lasing, the maximum output power is 1.14 W with an incident pump power of 4.7 W and a slope efficiency of 27%. In Q-switched operation, 1.1 mJ of output pulse energy is achieved at 200 Hz. The upper-state lifetime at different pulse repetition frequencies is also calculated.

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Solid-state lasers that emit in the eye-safe band of 1 500–1 700 nm have important applications in several aspects, such as range finding, spectroscopy, and Doppler wind lidar[1,2]. Crystals with Er^{3+} doping are promising active materials for such developments. Refractive index and thermal conductivity are important characteristics of a laser material. Er:GdVO$_4$ crystals possess a much higher thermal conductivity as well as a larger absorption and emission cross-section, making it a more promising laser material compared with other crystal hostsr[3,4]. Gabrielyan *et al.* recently reported an efficient room-temperature Er:GdVO$_4$ laser at 1 598.5 nm; the maximum continuous-wave (CW) output power of 3.5 W was achieved with resonant pumping by an Er-fiber laser at 1 538.6 nm[5]. However, Q-switched Er:GdVO$_4$ lasers have not yet been reported.

To the best of our knowledge, this letter is the first to demonstrate a new Q-switched Er:GdVO$_4$ laser that can operate at 1 598.8 nm. The pump of the propose laser is the signal of a MgO-doped periodically poled LiNbO$_3$ optical parametric oscillator (MgO:PPLN OPO) with a pump wavelength at 1 536 nm. In CW lasing, the highest output power was 1.14 W, with an incident pump power of 4.7 W and a slope efficiency of 27%. In Q-switched operation, 1.1 mJ of output pulse energy was achieved at 200 Hz.

The schematic of the experimental setup is shown in Fig. 1. The pump source of the MgO:PPLN OPO was a Yb:fiber laser (IPG, Germany). The Yb:fiber laser delivers up to 50 W of radiation at 1 064 nm, with an M^2 factor of 1.05. The half-wave plate was used to control the pump polarization for phase matching. The Yb:fiber laser beam was focused onto a waist radius of 65 μm at the center of the crystal using the lenses, L$_1$(f = 500 mm) and L$_2$(f = 1 000 mm). The OPO was based on a 50-mm-long grating period Λ = 30 μm MgO:PPLN crystal, and was configured in a linear cavity consisting of two plano-concave mirrors, M$_1$ and M$_2$ (r = 75 mm), and two plane mirrors, M$_3$ and M$_4$. All of the mirrors have $R > 99.8\%$ at 1.4–1.7 μm, $T > 95\%$ at 1 064 nm, and $T > 95\%$ at 3–5 μm. For OPO operation, we replaced mirror M$_4$ with an output coupler of T = 3.5% across 1.4–1.7 μm, as shown in Fig. 1. The total cavity length was 310 mm.

The Er:GdVO$_4$ crystal was 4 × 4 (mm) in cross section and 20 mm in length, and doped with 0.5 at% of Er^{3+}. Through liquid nitrogen cooling, the laser crystal functioned under a cryogenic temperature of 77 K. The measured pump absorption efficiency increased from 76% at 300 K to 98.2% at 77 K. Thus, 77 K was selected as the operating temperature to increase the absorbed pump power of the Er:GdVO$_4$ crystal. The pump source was the OPO signal at 1 536 nm. The diameter of the pump beam was focused to approximately 500 μm. A plano-concave geometry of approximately 150 mm comprising a plane pump input coupler with high transmission (> 95%) at the pump wavelength (1 536 nm) and high reflectivity (> 99%) at the lasing wavelength (1600 nm) was used. The output coupler was coated for 10% transmission at 1 600 nm, with 200-mm radius of curvature. The surface of an acousto-optic modulator (AOM) was anti-reflection (AR)-coated at the lasing wavelength. The AOM was mounted on a copper heat sink maintained at 20 °C with a thermoelectric cooler.

The MgO:PPLN OPO output power as a function of the incident pump power of the Yb:fiber laser is shown in Fig. 2. The slope efficiency was 40%. The output wavelength was obtained using a spectrum analyzer (WA-650, EXFO) combined with a wavemeter (WA-1500, EXFO). The spectrum of the MgO:PPLN OPO centered at 1 536.3 nm is shown in Fig. 3.

In the CW operation of Er:GdVO$_4$, the AOM was removed and the cavity length was fixed at 90 mm. The output power, as a function of the incident pump power

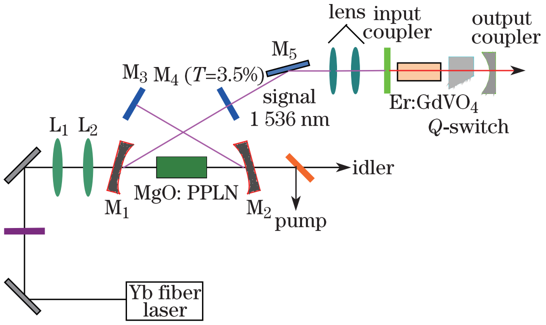

Fig. 1. Diagram of the experimental setup.

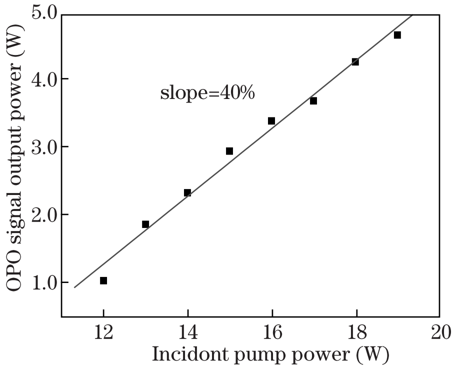

Fig. 2. OPO signal output power versus the incident pump power.

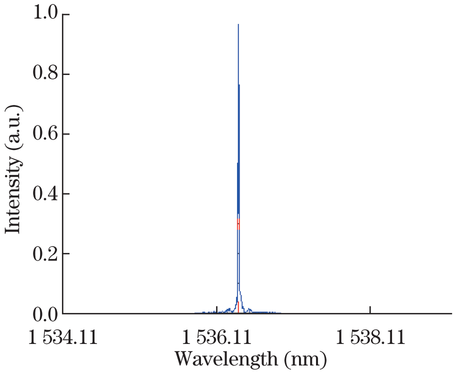

Fig. 3. Output wavelength of MgO:PPLN OPO.

on the Er:GdVO$_4$ crystals, is shown in Fig. 4. Under a 3.5% transmission of the output coupler, the maximum output power was 1.14 W, with an incident pump power of 4.7 W measured using a power meter (Coherent PM2). This value corresponds to a slope efficiency of 23% and an optical-to-optical efficiency of 27%. The spectrum of the Er:GdVO$_4$ laser centered at 1598.8 nm is shown in Fig. 5.

In the Q-switched operation, a higher transmission of 10% of the output coupler at 1 600 nm was used for lowering the intra-cavity energy fluence to avoid coating damage. The radius curvature of this output coupler was 200 mm, and the total cavity was increased to 150 mm. Figure 6 shows the average output power for both CW and Q-switch operations.

The dependence of output pulse energy on the repetition rate under a total incident pump power of 4 W is shown in Table 1. The highest output pulse energy (1.1 mJ) was achieved by the Q-switched operation at 200-Hz repetition rate. The expected dependence of the average power on pulse repetition frequency (PRF) for a CW-pumped Q-switched laser is given by

$$P_{\mathrm{av}}(\mathrm{PRF})/P_{\mathrm{av}}(\mathrm{CW}) = \tau_{\mathrm{s}}/\tau_{\mathrm{q}}[1-\exp(-\tau_{\mathrm{q}}/\tau_{\mathrm{s}})], \quad (1)$$

where $P_{\mathrm{av}}(\mathrm{PRF})$ is the average power in the Q-switched operation, $P_{\mathrm{av}}(\mathrm{CW})$ is the average power in the CW operation, τ_{s} is the effective lifetime of the upper state, and $\tau_{\mathrm{q}} = 1/\mathrm{PRF}$[6]. Using Eq. (1), the upper-state lifetime was calculated as a function of PRF at the pump power of 4 W, which was 1.77 ms for 200 Hz, 2.09 ms for 300 Hz, and 2.22 ms for 400 Hz. These values are much shorter than the Er radiative lifetime of 6.9 ms, which was published by Payne *et al.*[7]. These findings can explain the energy loss in Fig. 5. A lower PRF corresponds to a lower average output power obtained because of its shorter upper-state lifetime. This result may have been caused by the energy transfer-up (ETU) conversion, which can lead to a further increase in thermal loading and a significant reduction in energy storage

Table 1. Output Pulse Energy, Pulse Width, and Peak Power with Different PRFs

PRF (Hz)	Pulse Energy (mJ)	Pulse Width (ns)	Peak Power (kW)
200	1.1	28.2	39.2
300	1	32	31.25
400	0.9	35.1	25.7
500	0.77	42	18.3

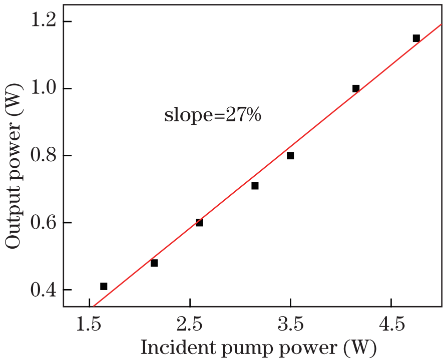

Fig. 4. Output power versus incident pump power.

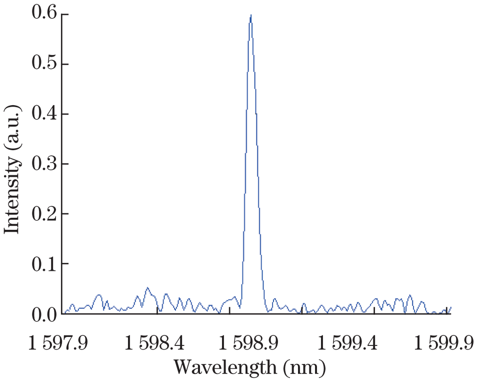

Fig. 5. Free-running spectrum of the Er:GdVO$_4$ laser at 1 598.8 nm.

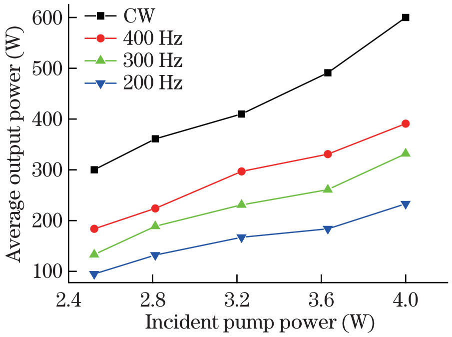

Fig. 6. (Color online) Average output power versus incident pump power with different PRFs.

time, particularly in the Q-switched mode.

In conclusion, we report a new Er:GdVO$_4$ laser pumped by a MgO:PPLN OPO. In the CW mode, 1.14 W of output power is achieved, and the slope efficiency is 27%. In the Q-switched operation, 1.1-mJ pulses with a pulse width of 28.2 are obtained at 200-Hz PRF, and the peak power is 39.2 kW. The upper-state lifetime of the Q-switched Er:GdVO$_4$ laser at different PRFs is also calculated. A lower-doped Er:GdVO$_4$ can achieve higher pulse energy because it can decrease the ETU, which will be the focus of our future studies.

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