Diode-pumped passively mode-locked Nd:KGd(WO$_4$)$_2$ laser with 1-W average output power

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Continuous-wave passive mode locking of a diode-pumped Nd:KGd(WO$_4$)$_2$ laser is demonstrated. The use of a saturable Bragg reflector as the mode-locking element permits the generation of 6.3-ps pulses, assuming a sech$^2$ pulse shape. An output power of 1 W was obtained, which corresponds to a slope efficiency of 34.5%. © 2002 Optical Society of America

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Over the past few years there has been increasing interest in the development of efficient diode-pumped sources of ultrashort pulses near 1 m based on the use of semiconductor saturable absorbers. Neodymium-(Nd-) doped glasses and crystals such as Y$_3$Al$_5$O$_{12}$ (YAG) and LiYF$_4$ (YLF) have been extensively studied for this purpose. Recently there have been reports of research on continuous-wave diode-pumped Nd-doped potassium gadolinium tungstate (KGW), which is an excellent candidate for the generation of ultrashort pulses at 1 μm. The fluorescence linewidth of the Nd ion in the KGW host lattice is twice that of the Nd ion in YLF, whereas the stimulated-emission cross section ($3.5 \times 10^{-20}$ cm$^2$) is larger than that of the Nd ion in YAG. Also, the broad absorption band (~10 nm) centered at 810 nm makes diode pumping possible and at the same time reduces the requirement for control of pump wavelength. Another attractive property of the Nd ion in KGW relates to its short upper-state lifetime ($1.3 \times 10^{-6}$ s), which, combined with its high emission cross section, will minimize the tendency of the laser to exhibit self-Q-switching dynamics when it is mode locked with a semiconductor-based slow saturable absorber. In addition, the low rate of change of refractive index with temperature ($0.4 \times 10^{-6}$ K$^{-1}$), compared with those of the YAG and YLF hosts, reduces thermal effects, which can distort an intracavity mode. Furthermore, the natural birefringence of the KGW host crystal leads to a polarized output. The broad emission linewidth of Nd:KGW (~720 GHz; Ref. 4) offers the potential for picosecond and subpicosecond pulses.

Despite these attractive features, there have been relatively few reports of mode-locked operation of Nd:KGW. Ultrashort pulses in the 8–15-ps range have been generated from flash-lamp-pumped Nd:KGW systems either by use of an acousto-optic modulator in conjunction with a nonlinear mirror or in a Q-switched regime by use of an organic dye as a saturable absorber. In diode-pumped systems, only the active technique of FM mode locking was used; it resulted in 12-ps pulses.

In this Letter we present what is, to the best of our knowledge, the first demonstration of passive mode locking of a continuous-wave diode-pumped Nd:KGW laser. The use of a saturable Bragg reflector (SBR) as the mode-locking element enabled us to achieve a considerable reduction in pulse duration compared with the previously reported values.

Our experimental configuration is shown in Fig. 1. The pump radiation was provided by a fiber-coupled laser diode (LD) operating at a wavelength near 800 nm. The output fiber had a diameter of 400 μm and a numerical aperture (N.A.) of 0.22 and was...
imaged onto the Nd:KGW crystal by two 50-mm focal-length lenses to produce a spot of 450-μm diameter. The plane–plane 3%-doped Nd:KGW crystal was 10 mm long and 3 mm in diameter. The crystal was wrapped in indium foil and placed in a water-cooled copper heat sink whose temperature was maintained at 14 °C. The crystal was cut such that the rod axis was oriented along the crystallographic b axis. The end of the crystal closest to the output fiber of the pump laser was coated with a dichroic mirror that was highly transmitting (HT) at the pump wavelength (~800 nm) and highly reflecting (HR) at the oscillating wavelength (~1060 nm). The other end of the crystal was antireflection (AR) coated at the oscillating wavelength. To minimize the thermal loading on the crystal we used a wing pumping scheme whereby we temperature tuned the oscillating wavelength of the pump diode to 800 nm. The pump absorption coefficient at this wavelength was estimated to be 1.1 cm⁻¹, which resulted in more than 66% of the pump radiation’s being absorbed by the crystal. To prevent a thermally induced stress fracture of the crystal we restricted the absorbed pump power to 3.4 W.

The optical resonator comprised the following mirrors: a 7% transmitting plane output coupling mirror; a highly reflecting plane folding mirror; a 1-m radius-of-curvature (RoC) folding mirror; a high-reflection coating on the crystal; a 75-mm radius-of-curvature folding mirror, and a plane mirror containing the SBR. The mode spot size on the SBR was calculated to be ~70 μm in diameter. The round-trip cavity length was 2.33 m, giving a repetition frequency of 64.5 MHz. The oscillation threshold was measured to be 0.5 W of absorbed pump power, and at an absorbed power of 3.4 W an average output power of 1 W was obtained, which corresponds to a slope efficiency of 34.5%.

The design characteristics of the saturable Bragg reflector (modulation depth, ~1%; recovery time, >100 ps) have been described in detail elsewhere, and with this structure self-starting, passively mode-locked operation was observed from the laser. As with other semiconductor absorber mode-locked systems the laser showed two distinct regimes of mode-locked operation. For absorbed pump powers in the range 1.2–1.7 W the laser generated Q-switched mode-locked pulses. Above 1.7 W, the Q-switched behavior disappeared and the laser generated stable trains of pulses. With ~3.4 W of absorbed pump power in the crystal, pulses as short as 6.3 ps, assuming a sech² pulse shape, with 1 W of average power were routinely generated. We believe that this is the highest average output power in continuous-wave mode-locked operation reported to date for the Nd:KGW material. The temporal and spectral profiles associated with the pulses are shown in Fig. 2. The spectrum, determined simultaneously with the autocorrelation, was measured by use of a high-finesse scanning Fabry–Perot interferometer. The spectrum was centered at 1067 nm and uses less than a quarter of the total available gain bandwidth (2.7 nm). The time–bandwidth product was calculated to be 1.07. This deviation from transform-limited operation (0.315 for sech²) is a common feature of the end-pumped systems and can be reduced by means of entering the soliton mode-locking regime. Unlike in the research reported in Ref. 4, we did not use any bandwidth limiting elements in the cavity to stabilize mode locking. Furthermore, no Raman shifting or upconversion within the Nd:KGW crystal was observed. This fact could be attributed to the relatively low peak intensity in the crystal (~21 MW/cm²) and high losses introduced by the cavity optics and saturable absorber.

The output power in our case is limited by the crystal geometry. It can be improved by changing to a thin slab design, which provides more-efficient thermal management of the crystal under conditions of high-power pumping. We also believe that, with proper cavity dispersion compensation or by use of other passive mode-locking techniques such as additive pulse mode locking that exhibit higher modulation depths, pulses in the subpicosecond range should be achievable.

In conclusion, we have demonstrated what is to the best of our knowledge the first continuous-wave passive mode locking of a diode-pumped Nd:KGW laser, using a saturable Bragg reflector. For ~3.4 W of absorbed pump power the total output power was 1 W, with a pulse duration as short as 6.3 ps at a repetition rate of 64.5 MHz. We believe that this is the highest...
average output power in continuous-wave mode-locked operation reported to date for the Nd:KGW material. Producing shorter pulses will require cavity dispersion compensation or other passive mode-locking techniques.

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Note added in proof: In our recent experiments with an additive-pulse mode-locked Nd:KGW laser we generated pulses as short as 1.9 ps, using the same crystal.11

References