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Monolithic Q-switched Cr,Yb:YAG laser

Yi Zhou [a,*], Quang Thai [a], Y.C. Chen [a], Shouhuan Zhou [b]

[a] Department of Physics and Astronomy, Hunter College and The Graduate School of The City University of New York, 695 Park Avenue, New York, NY 10021, USA
[b] North China Research Institute of Electro-Optics, P.O. Box 8511, Beijing 100015, PR China

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Abstract

We report the operation of a diode-pumped monolithic self-Q-switched Cr,Yb:YAG laser which generates 20 μJ pulses at 1030 nm with a pulse duration of 500 ps in a single longitudinal mode.
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Q-switching of microchip lasers is a simple way of obtaining short pulses with high peak power [1–6]. Using a solid-state gain medium of millimeter to sub-millimeter length end-pumped by a diode laser, laser pulses of microjoule to millijoule pulse energy are readily obtainable. Most of the studies on Q-switched microchip lasers have concentrated on Q-switched neodymium lasers using a chromium- or semiconductor-based saturable absorber. Recently, passively Q-switched microchip lasers using Yb^{3+} doped crystals combining with a Cr:YAG crystal or semiconductor antiresonant mirror have also been reported [7,8]. The peak power ranges from tens of Watt to 2 kW.

In this Letter, we report the operation of a high-peak-power monolithic Q-switched solid-state laser based on a new chromium and ytterbium co-doped YAG crystal. Yb:YAG is an attractive gain medium for microchip lasers owing to its long fluorescence lifetime for energy storage, broad absorption band for diode pumping and low thermal load for high efficiency [9–11]. Furthermore, the Yb ions in YAG do not exhibit concentration quenching and can be doped to a higher concentration for effectively absorbing the pump beam within the thin gain media. The use of co-doped laser crystals to act as both the gain medium and the saturable absorber for Q-switching was first demonstrated in Cr,Nd:YAG [2]. When the saturable absorber is distributed over the entire cavity length, single-longitudinal mode operation can be obtained regardless of the cavity length due to a reverse spatial burning effect [6]. The fold–fold

* Corresponding author. Tel.: +1-21-27-725-257; fax: +1-21-27-725-390.
E-mail address: yzhou@hunter.cuny.edu (Y. Zhou).

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symmetry in the saturation power of tetravalent chromium also provides polarization stabilization [12]. In the present study, the monolithic laser is made of a Cr,Yb:YAG crystal with strong saturable absorption to facilitate higher energy storage before Q-switching. We have attained single-frequency Q-switched pulses of 20 μJ pulse energy and 500 ps duration, which corresponds to a peak power of 40 kW, the highest ever obtained in microchip lasers with comparable pump powers and gain volumes. The intracavity energy density has exceeded the threshold of optical damage of commercial hard coatings.

The Cr,Yb:YAG crystal used in this study was grown using the standard Czochralski method. The doping concentration was 0.5 at.% for chromium and 5 at.% for Yb. Since the tetravalent chromium ions substitute aluminum in the garnet lattice, divalent calcium and magnesium were added for charge compensation. After growth, the crystal was subjected to an annealing process in the atmosphere to enhance the broadband absorption at 1 μm wavelength. The crystal was then polished to form a flat-parallel disk with the surfaces perpendicular to the ⟨1 1 1⟩ axis of the crystal. The room-temperature absorption spectrum of Cr,Yb:YAG is shown in Fig. 1. The spectrum is the superposition of a series of discrete absorption peaks of ytterbium and a broad absorption band of tetravalent chromium near 1 μm wavelength.

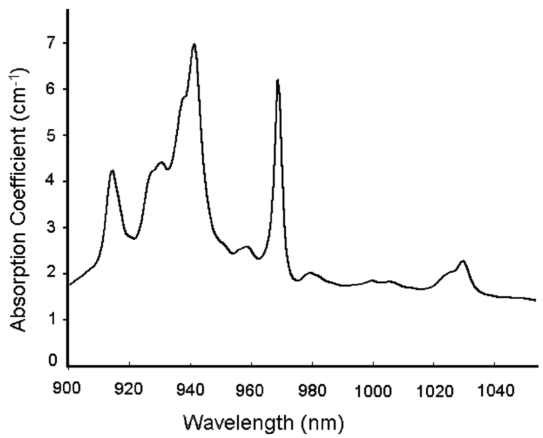

Fig. 1. Room-temperature absorption spectrum of Cr, Yb:YAG.

The absorption coefficient at the pump wavelength of 941 nm is 7.2 cm^{-1}. The absorption features at 1030 nm consist of a broad band attributed to the tetravalent chromium, and the ground-state absorption peak of Yb^{3+} at 1030 nm. By comparing with the absorption spectrum of Yb:YAG, we estimated that the absorption coefficient caused by Cr^{4+} was 1.2 cm^{-1}. To efficiently utilize the pump beam at 941 nm and minimize the ground-state absorption at lasing wavelength of 1030 nm, the laser cavity was chosen to be 750 μm so that the round trip length was equal to one absorption length at the pump wavelength. The surface facing the pump beam was coated for high reflectivity at 1030 nm and high transmission (>87%) at 941 nm. The output mirror was coated for high reflectivity $R = 90\%$ at the pump wavelength and 90% reflectivity at 1030 nm.

A fiber-coupled diode laser emitting at 940 nm wavelength with a core diameter of 100 μm and numerical aperture of 0.32 was used as the pump source. The pump beam was focused to the surface of the crystal. The diameter of the pumped region was measured to be 50 μm. Self-sustained repetitive Q-switching was observed when the pump power was 0.77 W. The pulse duration measured using a sampling oscilloscope and fast detector was 500 ps. Stable operation in a single longitudinal mode was obtained when the pulse repetition rates were less than 650 Hz. The laser pulses were linearly polarized with an extinction ratio of 10:1. The pulse-to-pulse power fluctuation was less than 0.5%, which is the resolution limit of the digital oscilloscope. As the pump power increased, the pulse energy remained nearly constant while the average power increased linearly. At a pump power of 0.9 W, the output exhibited a second longitudinal modes at every other pulse, and at a pump power of 0.95 W, a third longitudinal mode.

The pulse energy depends on the area of the pumped region. The maximum pulse energy attained was 20 μJ at which point, the dielectric coatings of the output mirror was damaged after every single shot. When the laser was operated near the threshold at 10 μJ pulse energy and at 2 kHz repetition rate, continuous operation was achieved but intermittently interrupted by optical damage. Similar optical damage was found in coatings made by difference commercial sources. Based the measured beam waist of 61 μm, the intracavity fluence at this point was 2.5 J/cm^2 in 0.5 ns, which exceeded the damage threshold of >15 J/cm^2 for 10 ns pulses or 0.75 J/cm^2 for 0.5 ns pulses for the dielectric coatings. The onset of mirror damage prevented a more detailed study at the present time. The problem of optical damage on mirrors can be alleviated by using Cr,Yb:YAG crystals of lower saturable absorption coefficients and output mirrors of lower reflectivity, which may result in lower pulse energy and longer pulse duration. The best compromise among pulse duration and pulse energy will depend on the application of the laser.

In conclusion, we have demonstrated the operation of a monolithic diode-pumped Q-switched Cr,Yb:YAG laser. Using a pump power of 0.77 W at 941 nm, the laser pulses have 10–20 μJ pulse energy with 500 ps pulse duration in a single frequency.

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