LETTER

High performance Cr$^{4+}$:YAG Q-switched CW diode pumped Nd:YAG laser

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This paper reports the operation of a Cr$^{4+}$:YAG Q-switched CW diode laser pumped Nd:YAG at 1064 nm. The laser performances resulted in 167 μJ, 21 ns pulses at 10 kHz, and 1.67 W power output. When intracavity polarized, stable amplitude (fluctuations < ±1%), TEM$_{00}$, 153 μJ pulses were generated allowing 50% SHG in KTP.

1. Introduction
To simplify the operation of high power solid-state lasers, improve their efficiency and compactness, and reduce their costs, passive Q-switching techniques can be usefully employed. Cr$^{4+}$:YAG Q-switching elements [1] (as well as a few other materials) have been developed and used with a variety of laser media. A great advantage of Cr$^{4+}$:YAG is its reliability and high damage threshold which makes it very attractive for high power operation. A high performance quasi-CW diode-laser pumped, passively Q-switched Nd:YAG has recently been demonstrated [2]. This paper reports the operation of a CW diode-laser pumped Nd:YAG laser at 1064 nm, passively Q-switched by a Cr$^{4+}$:YAG, generating 167 μJ, 21 ns pulses (full-width at half-maximum, FWHM) at up to 10 kHz repetition rate.

2. Experimental procedure and results
A 5 × 7 mm Nd:YAG rod, AR-coated at 1064 nm on one end, while coated for maximum reflectivity at 1064 nm and maximum transmission at 808 nm on the pumping end (Fig. 1), was used. The pumping fibre-coupled laser diode array (SDL 3450-P5) emitted 10 W at 808 nm from a 400 μm multimode fibre, and it was coupled into the Nd:YAG by a Cooke triplet. A plano–plano cavity was set up, with the Nd:YAG as rear mirror, which was stable because of the induced thermal lens. The characterization of the induced thermal effects is reported elsewhere [3]. The resonator length was 90 mm, and the pump spot size was adjusted to optimize the output power for CW operation. A mode radius of
was estimated in the Nd:YAG rod, at the maximum CW power of 2.7 W obtained with a 10% output coupler transmissivity. In these conditions, the thermal lens focal length was \( \approx 30 \text{ cm} \), and the beam quality was found to be \( M^2 = 2.7 \). From a standard Findlay–Clay analysis the linear losses were evaluated to be on the order of 2%, and the coefficient which relates the small-signal single-pass gain \( g_0 \) to the absorbed pump power \( P_{\text{abs}} \) was estimated to be \( K \approx g_0 / P_{\text{abs}} \approx 0.07 \text{ W}^{-1} \) (to within 10% accuracy). These results are consistent with the value of the optimum coupling (≈10%) measured experimentally at the maximum pump power.

Then the Cr\(^{4+}\):YAG sample was inserted into the cavity. The 1-mm long AR at 1064 nm Cr\(^{4+}\):YAG sample was supplied by CASIX, Inc. The sample had a low-intensity transmission \( T_0 \approx 86.3\% \) rising to 95\% under bleaching conditions. The non-linear transmission of the switch was tested at 1064 nm using a 2 kHz actively Q-switched diode-pumped Nd:YAG laser [4], which provided 70 ns long pulses, with \( M^2 \approx 1 \) and energy up to 350 \( \mu \text{J} \). The linearly polarized pulses were focused into the sample \( 1/e^2 \) radius in air at focus \( w_f \approx 60 \mu\text{m} \) and both incident and transmitted pulse energy were recorded. The transmission was measured as a function of the incident pulse fluence, and the results were interpreted using the model introduced by Koo \textit{et al.} [5], which includes the effect of excited-state absorption (ESA): for the absorption and ESA cross-sections of Cr\(^{4+}\):YAG at 1064 nm the values \( \sigma_a \approx 10 \times 10^{-19} \text{ cm}^2 \) and \( \sigma_c / \sigma_a \approx 0.20 \) were found, respectively, in agreement with recently reported measurements [6]. It is worth noticing that in Q-switching operation the maximum transmission of the saturable absorber was never reached, as the intracavity fluences were always lower than the saturation fluence \( \approx 1 \text{ J cm}^{-2} \).

The maximum output energy was obtained for the unpolarized laser, working with output coupler reflectivity \( R = 85\% \), at a frequency as high as \( f_R = 10 \text{ kHz} \). 167-\( \mu \text{J}, 21\text{-ns} \) single pulses were generated with ±5\% amplitude fluctuation. The average output power at the maximum pumping power was 1.67 W.

The amplitude instability of the output pulses which occurred with a regular alternating fluctuation was tentatively interpreted as being due to the interleaving of the polarization eigenmodes, which were excited because of the strong thermally induced birefringence and oscillated in the cavity with almost equal probability but with slightly different amplitudes. Indeed, the performances significantly improved after insertion of a polarizing plate (external polarization ratio >100:1) into the cavity (Fig. 1). The results of the operation of the polarized Q-switched laser are summarized in Figs 2 and 3.

Figure 2 shows the output energy and the pulse duration versus the pump power, obtained with the same output coupler reflectivity as before. Figure 3 shows the repetition