

LASERS

PACS numbers: 42.55.Rz; 42.60.Gd; 81.05.Mh
DOI: 10.1070/QE2012v042n03ABEH014745

High-peak power, passively *Q*-switched, composite, all-polycrystalline ceramic Nd:YAG/Cr^{4+}:YAG lasers*

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***Abstract*. High-peak power, passively *Q*-switched, composite Nd:YAG/Cr^{4+}:YAG lasers consisting of all-polycrystalline bonded Nd:YAG and Cr^{4+}:YAG ceramics are developed, and two applications of such lasers are discussed. A 1.1-at.%-doped Nd:YAG/Cr^{4+}:YAG ceramic laser is fabricated, which is quasi-cw pumped by a diode laser in the Hz-range, delivering laser pulses of 2.5-mJ energy and 1.9-MW peak power. By frequency doubling the laser output in a LiB_3O_5 (LBO) nonlinear crystal at room temperature, 0.36-mJ, 0.3-MW green laser pulses with 27% conversion efficiency are produced at 532 nm. Furthermore, a highly doped (1.5-at.%) Nd:YAG/Cr^{4+}:YAG ceramic laser operates successfully in the range of pulse repetition rates from 50 to 500 Hz, yielding 0.8-to-1.0 mJ pulses with a peak power around 1 MW. The laser output beam is amplified in a master-oscillator–power-amplifier (MOPA) system to generate laser pulses with 11-mJ energy at a 250-Hz repetition rate.**

Keywords: *neodymium lasers, passive Q-switching, ceramic lasers, diode laser pumping.*

1. Introduction

The advancement in ceramics technology has reached nowadays a maturity stage, especially in obtaining polycrystalline cubic laser media of high optical quality. The use of such laser media presents several key advantages: high concentration doping (especially for Nd^{3+} ions in yttrium aluminum garnet, YAG), easy fabrication of large-size ceramic samples, and low-cost mass production. A transparent polycrystalline Nd:YAG sample with optical characteristics similar to those of a single crystal was originally fabricated by a solid-state reaction method, and in 1995 the first laser emission at 1.064 μm was obtained from a 1.1-at.% Nd:YAG ceramics [1, 2]. A modified urea precipitation method enabled the development of large fine-grained ceramic Nd:YAG laser rods, used in a cw, 1.46-kW Nd:YAG ceramic laser with 42% optical-to-optical efficiency in 2002 [3]. Additionally, ceramics techniques allow realisation of multilayer laser components. CW output power of 144 W with 64% optical-to-optical efficiency was achieved from a composite, core-doped Nd:YAG ceramic laser in 2007 [4]. Recently, a quasi-cw pumped master-oscillator–power-amplifier (MOPA) system based on Nd:YAG ceramic rods delivered up to 1020 W of average power with about 30% optical-to-optical efficiency [5].

Ceramics technology enabled also fabrication of Cr^{4+}:YAG saturable absorber (SA) materials, and consequently passively *Q*-switch emission was reported from all-polycrystalline Nd:YAG-Cr^{4+}:YAG laser made of discrete

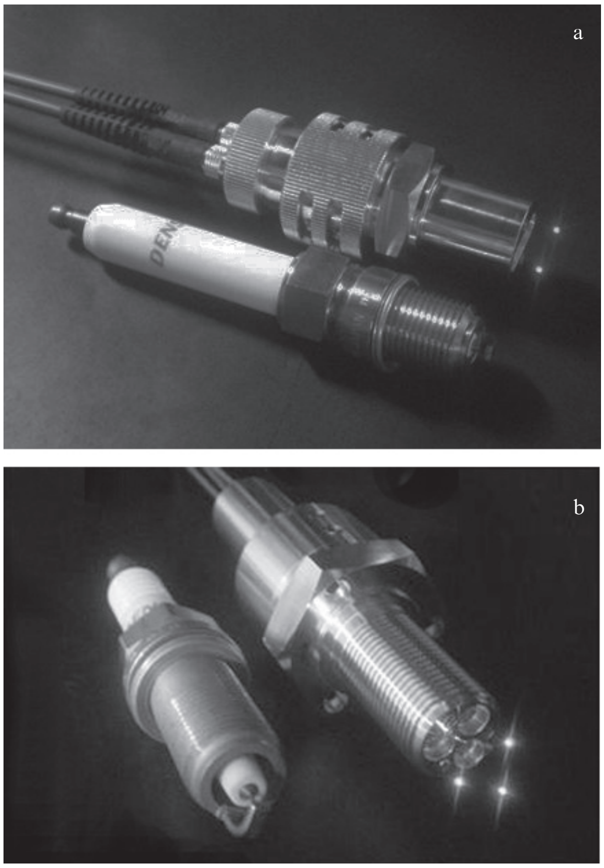

Figure 1. Composite Nd:YAG/Cr^{4+}:YAG ceramic lasers with (a) a two-beam output and (b) a three-beam output. Classical spark plug is given for comparison, and air breakdown is illustrated. (Courtesy of Prof. Dr. T. Taira of Institute for Molecular Science, Okazaki, Japan).

*Reported at XIX International Conference on Advanced Laser Technologies (ALT'11), Bulgaria, Golden Sands, September 2011.

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Received 4 October 2011
Kvantovaya Elektronika **42** (3) 211–215 (2012)
Submitted in English

elements [6] and from composite Yb:YAG/Cr^{4+}:YAG [7, 8] and Yb:YAG/Cr,Yb:YAG lasers [9]. In these works pumping was performed by a low output (few Watts) power, cw diode laser, and therefore laser pulses with low energy (E = 172 μJ) were obtained. Their duration t_p was 237 ps (peak power, 0.72 MW) and the pulse repetition rate was 3.5 kHz [8]. On the other hand, the repetition rate of pulses delivered by a passively Q-switched laser can be controlled via quasi-cw diode pumping. Employing this method and following some optimisation rules [10, 11], composite, all-polycrystalline, passively Q-switched Nd:YAG/Cr^{4+}:YAG ceramic lasers with a pulse energy up to 2.4 mJ and a peak power of 2.8 MW were realised [12]. The laser pulse repetition rate was controllable from a few Hz to 100 Hz, whereas the output consisted of two or three independent beams. These monolithic lasers, shown in Fig. 1, are considered to be a very good candidate for igniting internal combustion engines.

In this paper we report on the laser characteristics of composite, all-polycrystalline ceramic, passively Q-switched, Nd:YAG/Cr^{4+}:YAG lasers at different Nd-doping levels, and focus on two applications of such a laser device: (i) the laser can be used to generate high-peak power laser pulses in the green visible spectrum (λ = 532 nm) by extra-cavity, single-pass frequency doubling of the 1.064-μm fundamental laser radiation; (ii) a composite Nd:YAG/C^{4+}:YAG ceramic laser can be used as a master oscillator in a MOPA system, amplifying the pulse energy up to 11 mJ (peak power of ~12.8 MW) at a high (250 Hz) repetition rate.

2. Composite Nd:YAG/Cr^{4+}:YAG ceramic laser for generation of high-peak power laser pulses at 532 nm

The experimental setup is shown in Fig. 2. Pumping was performed by an 807-nm JOLD-540-QAFN-6A diode laser (Jenoptik, Germany) that was coupled to an optical fibre (diameter of 1.0 mm, numerical aperture NA = 0.39). The pump pulse repetition rate and pump pulse duration were 2 Hz and 250 μs, respectively. A pair of achromatic lenses was used to image the fibre end into Nd:YAG to a spot with 0.65-mm radius. The composite, all-polycrystalline Nd:YAG/Cr^{4+}: YAG ceramic medium (Baikowski Japan Co., Ltd.) consists of a 7.2-mm-thick, 1.1-at.% Nd:YAG ceramics bonded to a Cr^{4+}:YAG SA ceramics with the initial transmission T_0 = 0.30. The total length of the medium is 9.5 mm. About 95% of the pump is absorbed in the Nd:YAG ceramics, thus avoiding bleaching of the Cr^{4+}:YAG SA [13]. The surface S1 of Nd:YAG acts as the rear mirror of the laser. This mirror had a high-reflection (HR) coating (R > 99.8%) at the laser wavelength λ_{las} and high transmission (HT) (T > 98%) at the pump wavelength λ_p. The output coupler mirror (OCM) with 50% transmission at λ_{las} was coated on the surface S2 of Cr^{4+}:YAG.

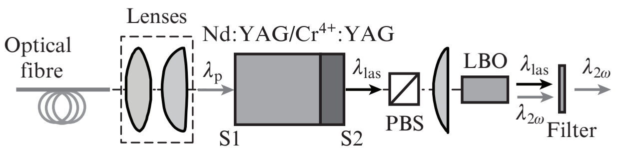

Figure 2. Scheme of a passively Q-switched, composite, all-polycrystalline ceramic Nd:YAG/Cr^{4+}:YAG laser.

The Nd:YAG/Cr^{4+}:YAG ceramic laser generated pulses with energy E = 2.5 mJ and 1.3-ns duration (FWHM), corresponding to a pulse peak power of 1.9 MW. The pump pulse energy E_p was equal to 32 mJ. The laser beam factor M^2 was determined by the knife edge method, and amounted to 3.15. Furthermore, the laser beam polarisation ratio (evaluated with a PBS polariser with extinction ratio of 100000 :1) was nearly 95%.

To analyse the laser characteristics, we used a numerical model in which the rate equation for passively Q-switched operation [14, 15] takes into account the influence of pump-beam spot size [12, 16]. The pump beam is assumed to have a top-hat distribution of radius w_p, and the laser beam to be Gaussian with a spot size of radius w_g. For better understanding, recall that the laser pulse energy is given by the general relation:

$$E = \frac{h\nu A_g}{2\gamma_g \sigma_g} \ln R \ln\left(\frac{n_{gf}}{n_{gi}}\right), \quad (1)$$

where $h\nu$ is the photon energy at λ_{las}; σ_g is the stimulated emission cross section of Nd ions; γ_g is the inversion reduction factor; A_g is the laser-beam effective area in Nd:YAG ceramics; and R is the OCM reflectivity. The initial population inversion density (i.e., the difference between the concentration of neodymium ions at the upper and lower working levels with account for their statistical weights) is

$$n_{gi} = \frac{-\ln R + L - \ln T_0^2}{2\sigma_g l_g[1 - \exp(-2a^2)]}, \quad (2)$$

where $a = w_p/w_g$; L represents the resonator round-trip residual loss; and l_g is the Nd:YAG thickness. The final population inversion density n_{gf} is related with n_{gi} by the equation

$$\left(1 - \frac{n_{gf}}{n_{gi}}\right) + \left[1 + \frac{(1-\delta)\ln T_0^2}{\beta}\right]\ln\left(\frac{n_{gf}}{n_{gi}}\right)$$

$$+ \frac{1}{\alpha}\frac{(1-\delta)\ln T_0^2}{\beta}\left[1 - \left(\frac{n_{gf}}{n_{gi}}\right)^{\alpha}\right] = 0. \quad (3)$$

Here $\delta = \sigma_{ESA}/\sigma_{SA}$; σ_{SA} and σ_{ESA} are the absorption cross section and excited-state absorption cross section of Cr^{4+}:YAG, respectively; $\beta = (-\ln R + L - \ln T_0^2)/[1 - \exp(-2a^2)]$; $\alpha = (\gamma_{SA}\sigma_{SA})/(\gamma_g\sigma_g)(A_g/A_{SA})$; γ_{SA} is the inversion reduction factor for Cr^{4+}:YAG ceramics; A_{SA} is the laser-beam effective area in Cr^{4+}:YAG ceramics. Additionally, we evaluated the focal length of the thermal lens, induced in Nd:YAG by optical pumping, with the model given in [17].

The dependences of the laser pulse energy E on the ratio $a = w_p/w_g$ are shown in Fig. 3. The spectroscopic parameters of Nd:YAG and Cr^{4+}:YAG used in the numerical model are taken from [12], whereas the resonator round-trip losses are considered to be 0.06 (0.01 for Nd:YAG and 0.05 for Cr^{4+}:YAG). Using the relationship $E_p = h\nu_p V_p n_{gi}$ ($h\nu_p$ is the pump photon energy, V_p is the Nd:YAG pumped volume) we calculated the pump pulse energy (Fig. 4).

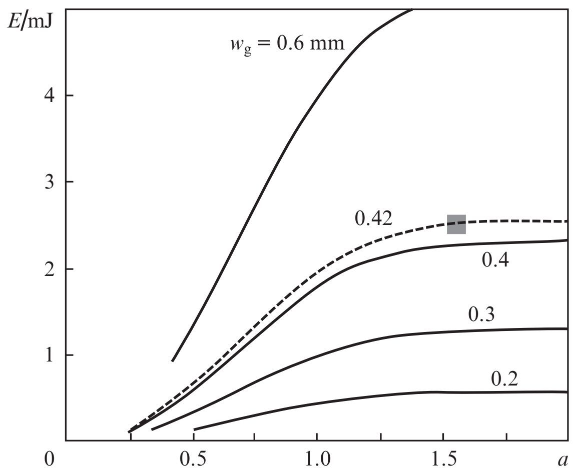

Figure 3. Dependences of the laser pulse energy at λ_{las} = 1.064 μm on the ratio $a = w_p/w_g$; square is the experimental result and curves represent the results of modelling.

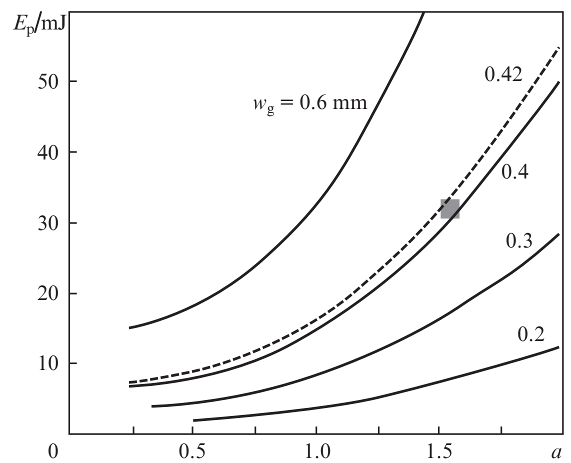

Figure 4. Dependences of the pump pulse energy on the ratio $a = w_p/w_g$; square is the experimental result and curves represent the results of modelling.

If the laser resonator is designed to keep the laser beam radius w_g constant, a low value of a (i.e. a small w_p) will ensure laser emission at reduced pump energies; however, in this case the laser pulse energy will be low. Both E and E_p increase with increasing pump beam spot size w_p. There seems to be a value beyond which any increase in w_p will not improve E, although E_p is increased. In this case, the central part of the inversion of population interacts with the laser mode, whereas the outside part will be depleted due to spontaneous emission, which results in heating of the laser medium [16]. Our calculations show that the focal length of a thermally induced lens in the 1.1-at.% Nd:YAG ceramics was ~90 m. The corresponding value of w_g found from the *ABCD* matrix analysis was ~0.42 mm. The agreement between modelling and experiments is good, especially if uncertainties in evaluation of Nd:YAG thermal lens and other physical or spectroscopic parameters of Nd:YAG and Cr^{4+}:YAG ceramics are taken into account.

We frequency doubled the output of the laser to 2ω=532 nm using single-pass, second harmonic generation in a 10-mm-thick LBO nonlinear crystal, designed for type I phase matching (θ = 90°, φ = 11.4°) at room temperature (25 °C). The LBO surfaces were AR coated for both λ_{las} and $\lambda_{2\omega}$. The beam was focused in the LBO nonlinear crystal through lenses with various focal lengths (between 100 and 150 mm), and a filter was used to separate the green light from the unconverted fundamental radiation. The energy of the linearly polarised fundamental beam was limited to 1.3 mJ in order to avoid the damage of the LBO crystal. The best results were achieved with a lens with a 125-mm focal length, focusing the 1.064-μm laser beam into LBO to a radius of ~0.74 mm. The energy of the second harmonic was 0.36 mJ, corresponding to 27% infrared-to-green conversion efficiency. This conversion efficiency is close to the results obtained by single-pass frequency doubling of a Nd:YAG-Cr^{4+}:YAG microchip laser with a BBO nonlinear crystal [18]: However, the green pulse energy obtained in our work is much higher, with pulse peak power reaching 0.3 MW. The combination of a high-energy, high-peak power microchip laser with a nonlinear material for second harmonic generation offers a simple way to produce MW-level, pulsed, visible laser radiation [19]. Moreover, efficient generation of laser radiation into the ultraviolet spectrum is possible.

3. Composite Nd:YAG/Cr^{4+}:YAG ceramic laser as a master oscillator in a MOPA system

A laser source with a high average power and high pulse energy in the mid-IR region (2.5 – 4.0 μm) is of interest for various scientific and industrial applications, such as remote sensing, molecular spectroscopy, or medical applications that make use of the efficient water absorption around 3 μm. Such a laser can be realised by employing an optical parametric oscillator based on periodically-poled stoichiometric $LiTaO_3$ [20]. The pump source for such a parametric device has to deliver high-energy (above 10 mJ), short (below 1-ns duration), high repetition rate (few-hundreds of Hz) laser pulses at 1.064 μm. The scheme of such a pump source (Fig. 5) consists of a two stage, double pass Nd:YAG rod amplifier. The master oscillator for the MOPA system is a composite, all-polycrystalline ceramic, passively Q-switched Nd:YAG/Cr^{4+}:YAG laser with high doping level of Nd.

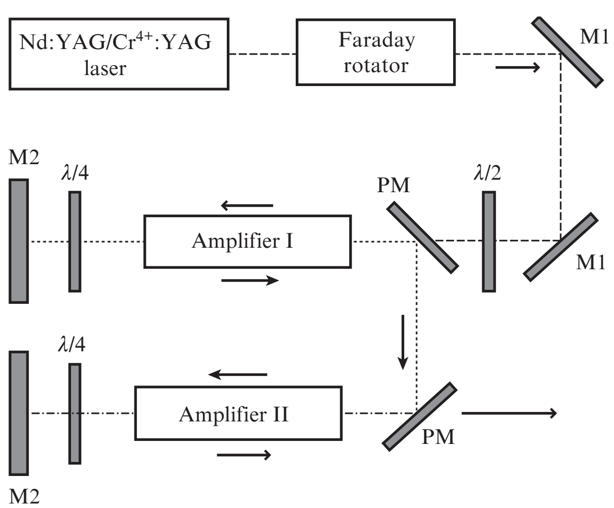

Figure 5. Scheme of a double-pass, two-rod Nd:YAG MOPA laser system: (M1, M2) mirrors; (PM) polarised mirror.

To decrease the oscillator pulse duration, we used a composite, all-polycrystalline Nd:YAG/Cr^{4+}:YAG medium, with Nd-doping level increased to 1.5 at.%. This allowed us to reduce the Nd:YAG thickness up to 5.2 mm, while maintaining high (~95%) absorption efficiency of the pump beam. The Cr^{4+}:YAG SA had similar characteristics as the Cr^{4+}:YAG ceramics used in Section 2. Finally, the Nd:YAG/Cr^{4+}:YAG medium was 7.5-mm thick, which is mandatory for obtaining laser pulses with duration below 1 ns. The composite medium was fixed in a copper holder at a temperature of 20 °C. As a pump source we use a fibre-coupled (600-μm diameter, NA = 0.22) diode laser (Jenoptik, Germany), and a 1:1 optical system to image the fibre end into the Nd:YAG. The pump pulse duration was 250 μs and repetition rate could be varied between 50 and 500 Hz.

At a pump pulse repetition rate of 50 Hz the Nd:YAG/Cr^{4+}:YAG laser yields 0.78 mJ, 860 ps pulses with a corresponding pulse peak power of 0.9 MW and a good beam quality ($M^2 = 1.32$).

By increasing the pump pulse repetition rate up to 500 Hz while maintaining the pump pulse duration constant, we were able to increase the laser pulse energy (Fig. 6). Laser pulses with energy up to 1.05 mJ were obtained at a 500-Hz repetition rate; in this case, the energy increased by ~35% compared to the energy measured at 50 Hz. Of course, this required also a rise in the pump pulse energy. The minimal energy E_p at 500 Hz was 13.8 mJ (i.e. by ~25% higher than the corresponding value measured at 50 Hz). The laser beam factor M^2 was 3.15, which indicates a decrease in the beam quality at a high repetition rate. Such behaviour (increase in E at high repetition rates) was also observed in passively Q-switched Nd:YAG/Cr^{4+}:YAG lasers made of discrete, single-crystal [21, 22] or composite ceramic [12] components. The main reason for this behaviour is the reduction of the Nd:YAG effective emission cross section [23] due to the increase in the medium temperature from thermal effects induced by the optical pumping.

The laser beam delivered by the composite Nd:YAG/Cr^{4+}:YAG medium was then amplified, using the MOPA configuration (Fig. 5). Each Nd:YAG rod (a single-crystal of diameter 3 mm and length 90 mm) had 0.6-at.% Nd doping, and was side-pumped with diode lasers. For a fixed repetition rate of 250 Hz, the energy of the laser beam measured after the Faraday rotator was 0.54 mJ. Double-pass amplification in the first amplifier stage increased this energy up to 3.6 mJ, and the final energy of the laser pulse after the second amplifier was measured to be 11.0 mJ (i.e. the peak power of ~12.8 MW). The characteristics of the laser pulses delivered by the MOPA system correspond to our initial goal. These characteristics can be improved by increasing the pump-beam absorption efficiency in the Nd:YAG rods of the MOPA system, by optimising the overlap between the input signal and the gain size in each Nd:YAG rod, or even by building a preamplifier stage.

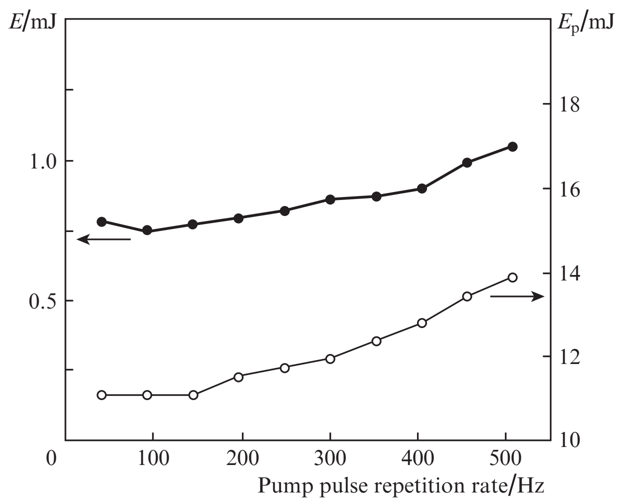

Figure 6. Laser pulse energy and pump pulse energy vs. pump pulse repetition.

4. Conclusions

We have reported on the output characteristics of composite, all-polycrystalline ceramic, passively Q-switched Nd:YAG/Cr^{4+}:YAG lasers. A 1.1-at.% Nd:YAG/Cr^{4+}:YAG laser is used to generate 0.36-mJ, 0.3-MW green laser pulses at 532 nm by single-pass frequency doubling of the 1.064-μm fundamental wavelength in an LBO nonlinear crystal at room temperature. This laser is a perfect candidate for obtaining high-peak power laser pulses in the visible and UV regions by single-pass nonlinear conversion. Furthermore, the laser pulses yielded by a highly-doped, 1.5-at.% Nd:YAG/Cr^{4+}:YAG ceramics can be amplified in a MOPA system. We have demonstrated a laser source that delivers high-energy (11 mJ), short (860-ps duration), high repetition rate (250 Hz) pulses at 1.064 μm and can be used for pumping an OPO system.

Acknowledgements. This work was supported by the Romanian Ministry of Research, Education and Youth (Project No. 72150/01.10.2008). Partial support from the Romania-Bulgaria bilateral project (455CB/20.10.2010 RO, DRG02-4/2010 BG) is acknowledged.

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