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A COMPACT ND:YAG SLAB AMPLIFIER FOR MINIATURE SOLID STATE Q-SWITCHED LASERS

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Александър Гайдарджиев, Димитър Драганов, Иван Бъчваров, Антон Трифонов, Торстен Фибих. КОМПАКТЕН ND:YAG УСИЛВАТЕЛ ЗА МИНИАТЮРНИ ТВЪРДОТЕЛНИ ЛАЗЕРИ С Q-МОДУЛАЦИЯ

Разработена е компактна Nd:YAG-базирана лазерна система, която генерира високоенергетични импулси със субнаносекундна продължителност и честота на повторение в килохерцовия диапазон при използване на конфигурация задаващ генератор–мощен усилвател. Системата е изследвана при ползване за задаващ генератор микрочипов лазерен осцилатор, излъчващ импулси с енергия 80 μJ и продължителност 600 ps, и миниатюрен осцилатор, генериращ импулси с енергия 1,6 mJ и продължителност 6,5 ns. Проектиран и конструиран е ефективен и компактен усилвателен модул, напомпван от четири 50 W лазерни диода. Паралелепипедната форма на активната среда позволява реализирането на пет-проходна геометрия на усилвателя. Получени са енергии на импулсите от 0,9 mJ и 8 mJ съответно при усилване лъчението на микрочиповия и миниатюрния лазер.

Alexander Gaydardzhiev, Dimitar Draganov, Ivan Buchvarov, Anton Trifonov, Torsten Fiebig. A COMPACT ND:YAG SLAB AMPLIFIER FOR MINIATURE SOLID STATE Q-SWITCHED LASERS

A compact sub-nanosecond Nd:YAG based high-energy kilohertz Master Oscillator Power Amplifier (MOPA) system has been developed. The system is seeded by two alternative master oscillators: a microchip laser emitting 80 μJ, 600 ps at 1 kHz and a Q-switched miniature oscillator with 1.6 mJ, 6.5 ns pulses at 1 kHz. We have developed a compact, five-pass gain module with slab design, pulsed pumped by four 50 W collimated laser diode bars. The amplified output energy is 0.9 mJ at 1 kHz, when seeded with the microchip laser and 8 mJ with the other master oscillator.

Keywords: solid state lasers, diode pumped, high energy, sub-nanosecond, slab and rod amplification

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1. INTRODUCTION

Ultra-compact and reliable laser systems providing both high-energy and high-peak power pulses at kHz repetition rates with diffraction-limited beams are desirable for a number of applications, e.g. new materials synthesis, remote imaging, chemical sensing, LIDAR[1, 2], materials processing[3,4], high efficient nonlinear optical conversion[5] and optical parametric processes[6]. The most common method for producing high-energy laser pulses with nanosecond and sub-nanosecond duration is Q switching. Recent significant advancements in Q-switched solid-state laser architectures became possible through the availability of high-power diode lasers that are being employed as pump sources. Especially in high-output and cost-effective solid-state systems one can employ QCW-diode-pumped amplifiers for boosting the output energy of Q-switched oscillators. The maximum value of the duty cycle of the pump pulse using qcw-diode-pump diodes is in order of 20 % which enables kHz repetition rate of the Nd-doped crystalline lasers. Generally, the pulse duration of a Q-switched laser decreases with decreasing cavity length. With cavity lengths ranging from millimetres to several centimetres, Q-switched diode-pumped lasers generate pulses with durations from a few hundred picoseconds (microchip laser) to several nanoseconds (miniature lasers)[7]. However, since the small gain volume limits the amount of energy that can be stored in the active medium, microchip lasers can reach only very modest output energy, typically up to hundreds of micro joules. For 1-micron Q-switched microchip laser either Nd:YAG (up to 500 μJ/pulse)[8, 9] or Nd:YVO4 (up to 330 and 800 μJ/pulse)[10, 11] can be used as active media for the amplifier. The choice of the material is dictated by the targeted pulse energy and repetition rate. For example, Nd:YVO4 exhibits a larger emission cross section and a lower saturation fluence. Hence it is a better choice for up-scaling the output power of an oscillator with pulse energies ranging from a few to several tens of micro joules. On the other hand, Nd:YAG has a lower amplification gain than Nd:YVO4 but shows favourable mechanical and thermal properties, in addition to a longer excited-state lifetime. Consequently, Nd:YAG is the preferred gain medium for high-energy (1-10 mJ at 1 kHz) miniature laser systems.

In this work, we present a compact multipass slab laser amplifier used in a Master Oscillator Power Amplifier (MOPA) configuration for up-scaling the output pulse energy of miniature diode-pumped Nd:YAG lasers to 1-10 mJ. The slab geometry ensures high gain, excellent for small signal amplification which, combined with the multi-pass design, can be used to extract a large fraction of the stored energy in the laser media while operating in TEM_{00} mode [12]. The amplifier module, described here, comprises of a Nd:YAG slab with 1% at doping, side-pumped by four 808 nm collimated laser diode bars. As a seed source (oscillator) we use a diode-pumped Nd:YAG single-frequency microchip laser (Standa Inc.) emitting 80 μJ of linearly polarized, TEM00 (M2 = 1.2) radiation with 0.6-ns

(FWHM) pulse width at 1 kHz. A two-lens optical relay system is used to adjust the seed beam diameter waist to 0.4 mm in the amplifier medium, in order to exactly match the height of the pumped zone inside the active element. The amplifier module was seed alternatively by home made electro-optically Q-switched short cavity laser oscillator emitting TEM00 pluses with up to 1.5 mJ pulse energy and ten times longer pulses than those of the microchip laser.

2. EXPERIMENTAL SETUP

2.1. Short-pulse master oscillator

The possibility to generate very short pulses at high repetition rates in Q-switched neodymium lasers was demonstrated by Plaesmann et al.[13], who reported pulse durations of 1 to 11 ns while operating a Nd:YLF laser at 10 to 100 kHz rates. The average power was limited to ~ 70 mW. The short pulse width of this laser was determined by the very short (<10 mm) resonator length. However, the short resonator length requires the incorporation of a miniature acousto-optic Q-switch with significantly reduced diffraction efficiency and, hence, hold-off. In our experimental setup we employed two different oscillators: microchip laser and a home made miniature q-switched laser.

In order to obtain high output power and sufficiently short pulses, we have constructed a master oscillator with 155-mm resonator length (Fig.1), employing a 12-mm BBO Pockels cell as an electro-optic modulator. The high voltage Pockels cell driver easily supports tens of kHz repetition rates. The active element is 8-mm long Nd:YAG crystal end-pumped with up to 16 mJ, 1 kHz, 180-μs pulses from a fibre-coupled, 808-nm diode laser (JOLD 70 QPXF 1L). The oscillator is designed so that the pump beam size (around 600 μm) in the active element is equal to the fundamental TEM_{00} mode size of the cavity. Also, we have implemented a scheme with intracavity Dove- and Porro prisms (see Fig.1) in order to increase the stability of the resonator [14] against optical misalignment. As a necessary condition that ensures the efficiency of this method, the rear mirror mount and the optical coupler mount were assembled on a common rigid mechanical base. Experimentally was proven, that when the common base is tilted in the range of ±20 mrad in both the vertical and horizontal plane, the output energy of the oscillator does not change substantially. Hence, this scheme is largely insensitive to misalignments caused by bending or twisting of the oscillator mechanical chassis.

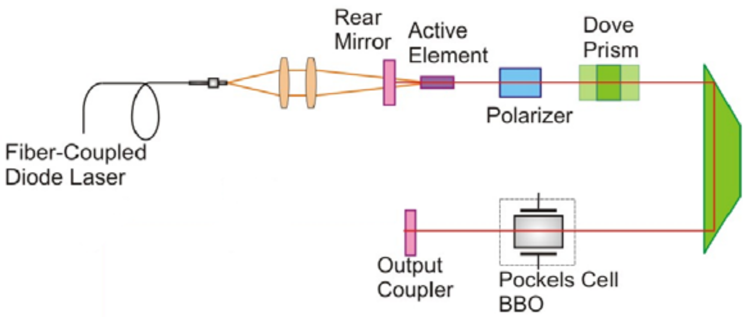


Fig.1. Master oscillator schematic layout. The active element is an 1% Nd:YAG rod with 3 mm diameter and 8 mm length, fiber diameter is 600 µm, NA = 0.22, cavity length 155 mm, Porro prism bending the oscillator, 60 % transmission flat output coupler and a 12-mm BBO Pockels cell

In free running mode, the oscillator optical to optical efficiency was 26% e.g. the maximal output energy was 2.5 mJ at 9.5 mJ pump (Fig. 2a). However, in Q-switch regime we limited the pump energy so the output energy not to exceed 1.5 mJ (at 1 kHz repetition rate) in order to avoid optical damage of the used intracavity elements. We found the laser pulse duration (around 6 ns) is practically independent from the pump pulse energy in the entire pump range. The oscillator is compact and reliable suitable for industrial applications.

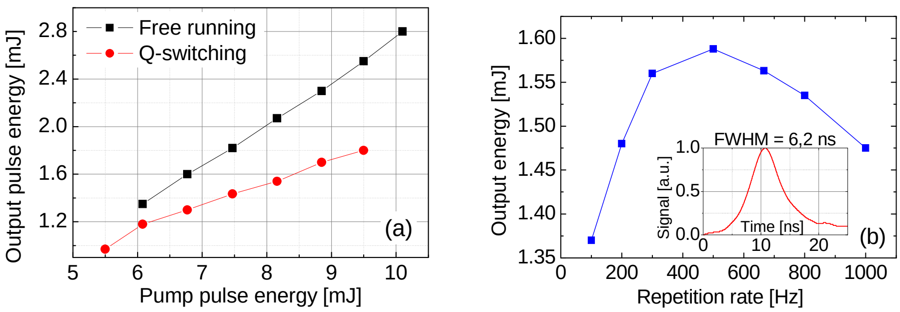


Fig. 2. (a) Master oscillator pulse energy versus the pump pulse energy performance. Pump pulse duration 180 µs, repetition rate 1 kHz. (b) Master oscillator output energy as a function of the repetition rate. Inset shows a typical time profile of the oscillator output pulses

The spatial distribution of the intensity in the output beam spot shows that the laser operates in single transverse mode with M2 below 1.6. The duration of the output pulses at 9.5 mJ pump energy is 6.2 ns FWHM (see inset Fig. 2b). In addition, the output energy dependence on the repetition rate shows maximum around 500 Hz (Fig. 2b). However, the output energy decreases slowly (6 %) towards 1 kHz repetition rates.

As an alternative approach to the home made master oscillator we employed a diode-pumped Nd:YAG single-frequency microchip laser (Standa Inc.) as a seed source. The laser comprises of a power supply unit including a laser diode (LD) driver, fiber pigtailed LD, and internal pulse generator. The laser operates in internal trigger mode and is used to trigger the laser diodes pumping the amplifier. Due to the very short cavity length (around 8 mm) the microchip resonator operates in single frequency mode. The laser is passively q-switched using Cr4+:YAG. It is emitting 80 μJ of linearly polarized light (polarization ratio better that 100:1), TEM00 mode (M2 = 1.2) with 0.6-ns (FWHM) pulse width at 1 kHz. The power stability is ±1.5 percent over six hours. This alternative solution compensates the inherent low pulse energy through with more robust design (practically impossible to misalign), ensuring reliability and even more compact size with much shorter pulse durations.

2.2. Nd:YAG slab amplifier module

We have constructed a Nd:YAG slab amplifier module comprising of a 30x8x1.5 mm 1% Nd doped crystal transversely pumped by four 808 nm, 50 W collimated laser diode bars (Osram SP LG81) operated in pulsed regime (Fig. 3). The active element was mounted on an actively-cooled copper heat sink. The laser diodes were mounted in specially designed holders made from high temperature resistant polymer, and thermally stabilized by a water cooling circuit. The diode bars were driven by a pulsed-current driver delivering up to 55-A current pulses with variable duration and frequency. The fast-axis microlense collimation of each diode bar radiation ensures less than 1 degree divergence, resulting in an almost constant 8.5x0.4 mm beam over the whole width of the active element. The crystal absorption of the pump is close to 90 %.

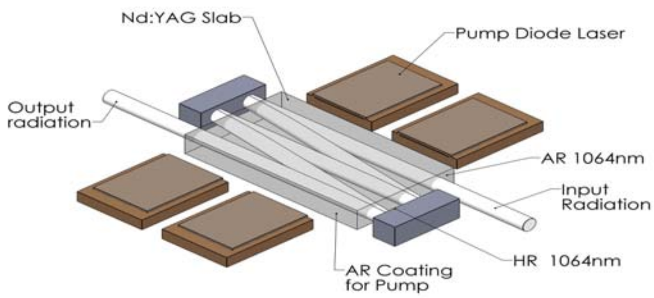


Fig. 3. Scheme of the Nd:YAG slab amplifier module

Special precautions were taken to ensure that the emission of all four diode bars lays in one plane, parallel to the cooled surfaces of the crystal. The diode bars were offset in such fashion to avoid direct irradiation of the emitters from the opposing sides. A system of two lenses was used to contract the 1mm beam diameter from the master oscillator to 400 μm, thus ensuring maximal overlap between the pumped height of the active element and the beam. The beam profile on entering the amplifier was close to round, but during propagation in the active media it is becoming elongated in the plane of pumping, which additionally enhances the amplifier efficiency by improving the overlap between the pumped volume and the amplified beam.

2.3. Amplifier model

Our modelling of the amplifier performance has been based on experimental estimation of the small signal gain dependence on the input energy and subsequent application of the Franz-Nodvik theory for the amplifier gain. In order to obtain the gain coefficient we used a relationship between the small signal gain (g_0), single pass gain (G_0) and diode pump input energy (E_p), which is known to be[15]:

$$\ln G_0 = g_0 l = K E_p, \qquad (1)$$

where K is an energy conversion factor accounting for: transfer of the pump radiation to the gain medium, absorption of the pump, Stocks shift, quantum efficiency, overlap between the beam and the gain region and the storage efficiency. Following a method first proposed by Findley and Clay[16], the conversion factor K, i.e., the small signal gain of a resonator can be obtained experimentally by using output mirrors with different reflectivities and determining the threshold energy for lasing at each mirror configuration. The relationship between output coupler reflectivity, resonator losses and threshold pump energy incorporates information for the resonator conversion factor K and is given by:

$$-\ln(R) = 2KE_{th} - L, \qquad (2)$$

where R is the reflectivity of the output coupler and E_{th} is the input energy at threshold, L are the resonator losses. We used the amplifier in a resonator regime with rear mirror and output coupler as close as possible to the active medium in other to minimize the effects of the thermal lens on the measurement, thus keeping the losses constant over the used range of the pump power. In order to determine the small signal gain we measured the threshold energy with four different output couplers with corresponding reflectances of 15%, 25%, 30% and 40%; the results are shown on Fig. 4.

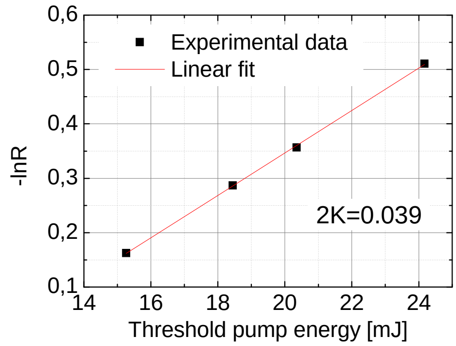


Fig. 4. Measurement of the resonator conversion factor encompassing all the efficiency factors involved in the energy transfer mechanism of the laser

Given by the slope of a straight line fit the resonator conversion factor for our amplifier configuration can be calculated. In our case it is 0.039 with 10 % error due to the threshold energy measurements. Hence, the energy conversion factor K is equal to 0.0195. Using a rate equation analysis, and making the simplifying assumption that the pulse is short (i.e., no amplifier pumping or gain relaxation processes during the pulse), Franz and Nodvik[17] showed that the amplifier gain (G) for a laser pulse could be expressed in the form

$$G = \frac{E_s}{E_{in}} \ln\left\{1+\left[\exp\left(\frac{E_{in}}{E_s}\right)-1\right]G_0\right\}. \tag{3}$$

This expression represents a relationship between the gain G for the pulse, the oscillator input pulse energy density E_{in}, saturation energy density E_s and the initial small signal gain G_0. Here $G_0=\exp(g_0 l)=KE_p$, g_0 being the SSG coefficient and l is the length of the active medium; E_{in} is the input pulse energy per unit area, i.e., energy fluence entering the amplifier.

And for a 4-level system with fast lower level relaxation the saturation fluence is given by

$$E_s = \frac{h\nu}{\sigma}, \tag{4}$$

h is Planck's constant, ν is the frequency of the laser wavelength, σ is the stimulated emission cross-section. The stimulated emission cross section of Nd:YAG[18] is taken to be $4.3\text{x}10^{-19}$ cm^{-2} thus for the saturation fluence we acquire 0.43 J/cm^2. We analyzed one, three and five passes through the amplifier. The dimensions of the gain medium allowed even at five pass scheme no considerable overlap of the different passes through the amplifier, thus no gain depletion is considered. By subsequent application of equation (3) with the estimated value of

G_0 we were able to estimate the gain at different pump levels and to make a comparison with the experimental data shown below on Fig. 6b.

3. RESULTS AND DISCUSSION

Using an input energy of 80 μJ (into the slab amplifier module) from the microchip laser and 250-μs pump pulses (at 55 A, pump peak power 50 W) from the bars, we are able to produce up to 0.9 mJ pulse energy at 1 kHz, with near-diffraction-limited beam quality. The output pulse duration (measured with InGaAs PIN photodiode and 5-GHz analog oscilloscope) was found (unchanged) to be 0.6 ns. In this case, we are able to obtain 11-fold amplification of the microchip laser energy with five passes through the active medium, while preserving the beam quality and pulse duration. The output pulse dependence on the pump energy is shown on Fig. 5.

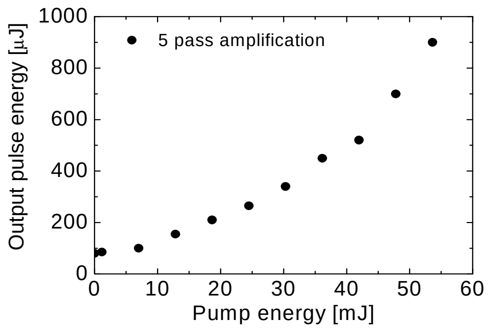
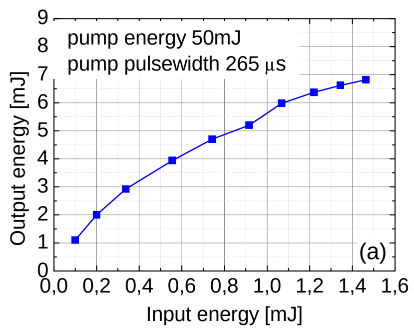


Fig. 5. Output energy vs. pump energy for five-pass amplification of microchip laser. The amplifier input is 80μJ, 600 ps at 1 kHz

To illustrate the amplifier's ability to work with the commercially available Q-switched lasers with millijoule output and ~5 ns pulses, we studied the amplification (in the same setup) of the output from the home-built an industrial-grade electro-optically Q-switched Nd:YAG laser to produce up to 8 mJ pulse energy at 1 kHz, with diffraction-limited beam quality. The slab module was operated as an unsaturated, five-pass amplifier. Both the oscillator and the slab amplifier were operated in quasi-cw mode, with pump-pulse durations of 180 μs and 265 μs, respectively. The Q-switched laser pulses were synchronized to arrive at the end of the pump pulse for the corresponding amplifier. We first measured a single-pass gain of the Nd:YAG amplifier without the folding high-reflective mirrors (see Fig. 3). The two goals of these measurements were to verify our gain modelling and to determine the uniformity of the gain distribution. Using a 1 mJ oscillator beam we probed the single-pass gain at ~200 W of total peak pump power. The gain was found uniform throughout the entire pumped cross section of the slab and it equal to 1.6 which is 18% smaller than the calculated value 1.9 using relation (3). We attribute this difference due to the overlapping between the pump region in the slab and input beam which are not taken into account in the method of K measurement.

We then measured the output energies from the Nd:YAG amplifier as a function of the pump power at different input energies in three- and five-pass geometry. The data plotted in Fig. 6b show that using five-pass configuration and 1.25 mJ input beam, we achieved output energy of 7.5 mJ. With three-pass configuration, the maximum output energy was substantially lower, 4.3 mJ. This is indication of the lack of gain saturation. Thus, an employment of a second amplification stage, identical to the used one would result in even higher output energy. Unfortunately, due to the necessity to contract the beam size to 400 μm and the low damage threshold (<500 MW/cm^2) of the coatings on the used slabs, an increase of the output energy above 10mJ was not possible. The output beam was elliptical (2x0.4 mm) with nearly Gaussian profiles in the vertical and the horizontal plane.

The result of the conducted calculations of the Nd:YAG output energy as a function of input energy is plotted on Fig. 6b. Also plotted are the corresponding experimental data that are in good agreement with the predicted values. In particular, the maximum energy obtained was 8 mJ, only 2 mJ less than the predicted value.



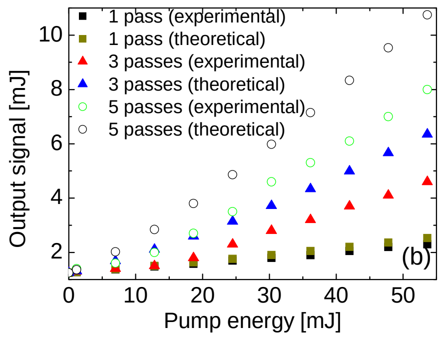


Fig. 6. (a) Output energy dependence on the input energy at a fixed pump energy level and pulse width in five pass configuration. (b) Comparison between the results from the theoretical model described in section 3.2 and the measured output energy vs. pump energy for single pass, three passes and five passes in the amplifier

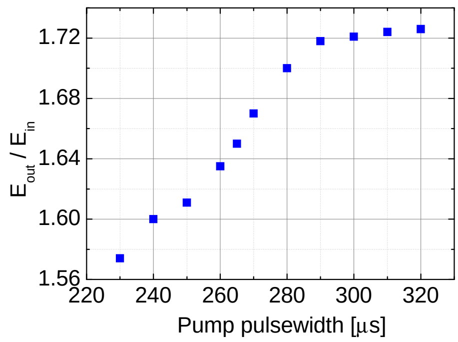


Fig. 7. Amplifier gain (output energy to input energy ratio) in dependence of diode laser pump pulse duration

The dependence of the amplifier gain on the diode pump pulse duration (Fig. 7) shows that pumping around 270−280 µs is optimal. Pumping with longer pulse duration is not beneficial because of the limited lifetime of Nd:YAG. However, from the plot in Fig. 7 it is obvious that there is possibility to increase further the pump pulse width but it will be at the cost of reduced efficiency. Longer pump durations than 300 µs are neither effective nor will give any increase of the output power. Finally, around 70% of the output light is linearly polarized, the depolarization is due to the thermally induced birefringence in Nd:YAG.

Additionally, the constructed amplifier is capable to efficiently amplify even very weak signals. For example with 80-µJ input (typical for microchip lasers) we have more than ten times amplification to the mJ level (Fig. 6a). Therefore employing this approach could overcome the main disadvantage of the microchip lasers— the low output energy, and could make laser systems with sub-nanosecond pulse duration operating in single-frequency regime with energy in the mJ range easily available. By implementation of a second slab amplifier, further increasing of the output energy is feasible.

4. CONCLUSION

In conclusion, we have designed and constructed a compact, reliable Nd:YAG slab amplifier with two alternative seed sources. The performance of the amplifier was tested by using a microchip laser and a 155-mm cavity miniature laser. The obtained output energy in both cases were 0.9 mJ (80 µJ, 600 ps, 1 kHz input) and 7.9 mJ (1.45 mJ, 6.5 ns, 1kHz input) respectively. Currently, we are planning to add a second amplification module to the microchip system in order to generate 10 mJ-pulses with sub-nanosecond time duration.

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