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Generation of Picosecond Laser Pulses at 1064 nm from All Solid-State Passively Mode-Locked Lasers

Do Quoc Khanh, Nguyen Trong Nghia, Pham Long, Trinh Dinh Huy, Nguyen Dai Hung

Center for Quantum Electronics, Institute of Physics, VAST
10 Dao Tan Street, Ba Dinh Dist., Ha Noi, Vietnam

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Abstract: Using semiconductor saturable absorber mirror and diode end-pumping configurations, all solid-state passively mode-locked Nd^{3+}:YVO_4 lasers have been successfully developed. The lasers efficiently provide a stable train of ultra-short laser pulses of 12 ps at 1064 nm at the pulse repetition rate adjustable from 8.8 MHz to 100 MHz. The peak power of 1.3 kW and an average laser power of 940 mW were obtained at the pulse repetitive rate of 60 MHz, corresponding to a laser conversion efficiency of 43%. In order to obtain lower pulse repetitive rate and, therefore, higher peak power, a long laser resonator (larger than 15 m) is proposed and successfully developed for diode end-pumped passively mode-locked laser operation using a simple multiple-pass cavity configuration. As a result, the peak laser power up to 5.1 kW was obtained at the pulse repetitive rate of 8.8 MHz. The experimental results of the picosecond laser amplification and the harmonic generations at 532 nm (2nd), 355 nm (3rd) and 266 nm (4th) are presented.

Key words: laser diode pumping, passive mode-locking, solid-state laser.

I. INTRODUCTION

Ultrashort pulsed lasers have been widely applied for the time-resolved measurements in physics, chemistry and biology. By the progresses in directly diode-pumped solid-state laser material and by the appearance of a semiconductor saturable absorber mirror (SESAM) mode-lockers, compact ultrafast SESAM mode-locked all-solid laser systems have been strongly developed and dominating the ultrashort solid-state laser market for scientific, technological and medical applications [1-4]. This paper presents the results obtained in the development of CW diode-pumped ultrashort solid-state Nd:YVO_4 lasers passively mode-locked with a semiconductor saturable absorber mirror (SESAM). The parameters of SESAM, resonator, optical element and diode laser end-pumping configurations have been researched for stable, highly efficient, passively mode-locked laser operations, using commercially available components. The diode-pumped passively mode-locked solid-state Nd:YVO_4 laser generates a stable train of ultra-short laser pulses (12 ps, 8-100 MHz at 1064 nm).

II. EXPERIMENTS

II.1. Cavity configuration

For a generation of ultrashort laser pulses based on the mode locking techniques, two basic conditions have to be satisfied. Firstly, a laser must generate a fairly large number of longitudinal modes. Secondly, these modes must be equidistant in frequency and synchronized in phase.

In order to satisfy the first condition, a nonselective and sufficiently long laser resonator has been developed for the simultaneous excitation of a sufficiently large number of longitudinal modes. In this case, the multi-frequency generation is very important. Furthermore, the interference of m longitudinal modes which are equidistant in frequency and phase locked leads the laser emission to be the nature of a train of ultrashort pulses which follow one another with time interval T equal to the resonator round-trip time

We have chosen the laser medium of Nd:YVO_4 that is very efficient and robust as well as easily provided by a number of suppliers. The crystal has a gain line width of about 10^{12} Hz corresponding to minimum obtainable pulse duration of a few picoseconds. The resonator configuration of laser diode-pumped mode-locked $Nd:YVO_4$ laser is shown in Fig. 1.

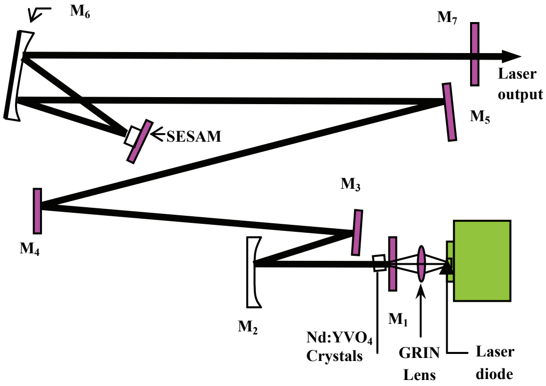

Fig. 1. Cavity configuration of the laser diode-pumped passively mode-locked $Nd:YVO_4$ laser

The pump source is a CW diode laser (ATC, Russia) emitted at the wavelength of around 808 nm with a variable output power from 0 to 2100 mW. Active cooling and temperature stabilization is provided by a built-in Peltier cooling device. The polarization of the laser light is horizontal. The diode has a built-in cylindrical micro lens for its fast axis collimation. This allows us to use simple pump optics, consisting of a single lens of 25 mm focus length. The rear mirror M_1 is a dichroic flat mirror ($R > 99\%$ @1064 nm and $R < 5\%$ @808 nm). The crystal is a $3 \times 3 \times 3$ mm, a-cut, 1% doped AR/AR coated Nd:YVO4 (Casix) and mounted on a copper heat sink. The Nd:YVO4 was oriented for maximum absorption at 808 nm and titled by about 4-5 degrees with the optical axis in order to avoid the etalon effect. M_2 is a concave mirror of radius $R = 30$ cm, it allows to get the best overlap between the pumped volume and the laser mode, and minimize intracavity diffraction losses. M_3, M_4 and M_5 are flat mirrors, high reflection at the laser wavelength of 1064 nm. M_6 is a concave mirror with radius $r = 15$ cm and used to focus the intracavity laser energy to the saturation fluence of the SESAM.

- ***Mode-locking laser operation***

For phase locking of longitudinal modes, we have used the passive locking method with a semiconductor saturable absorber mirror (SESAM) in the resonator. As presented in Section II.1, the SESAM has a relaxation time much smaller than the resonator round-trip time. Therefore, intra-cavity laser energy is able to bleach the SESAM at a modulation period of about $c/2L$ (c – light speed in the resonator and L – resonator length) and leads a mode-locking laser operation.

The threshold of the CW $Nd:YVO_4$ laser was obtained at the diode pumping power of 150 mW. When the diode pumping energy is less than 540 mW, the intracavity laser energy was too low compared to the saturation fluence of the SESAM and the laser might run in CW. Increasing the diode pumping energy, the intracavity laser energy increases and reaches to the saturation fluence of the SESAM. This leads the laser behavior to be either Q-switched mode-locking (Fig. 2).

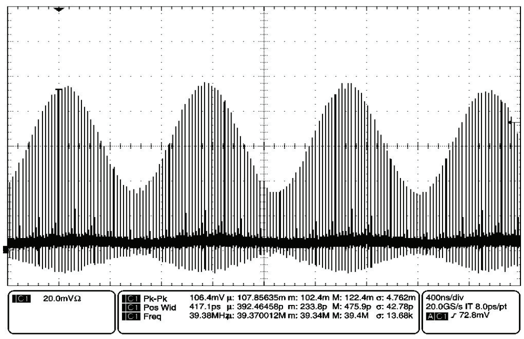

Fig. 2. Q-switch mode-locking operation

Increasing the diode pumping energy more than 540 mW the laser operates in pure mode-locking (Fig. 3). In practice, the pure mode-locking laser operation is quite far above the lasing threshold. A stable mode-locking laser operation was obtained with the diode pumping powers larger than 1500 mW. The pulse energy stability is rms. ± 2%.

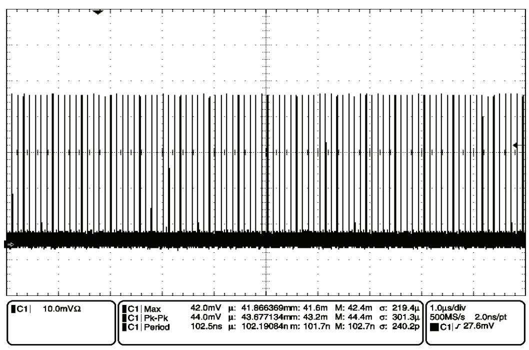

Fig. 3. Mode-locking operation

Figures 2 and 3 present the pulse trains obtained from the mode-locked $Nd:YVO_4$ laser with a fast photodiode (rise time < 200 ps) and a digital oscilloscope (Tektronix 1.5 GHz, 20 GS/s).

- ***Power characteristic and pulse width of mode-locking laser***

The power characteristic of mode-locking $Nd:YVO_4$ laser are measured with two different output mirrors (reflectivity of 80% and 94%), as shown in Fig. 4. In mode-locking laser operation, considerably high laser efficiency was achieved. At a maximal pumping power of 2200 mW and the output mirror of 80%, we obtained the laser power of 940 mW corresponding to laser efficiency up to 43%. With the output mirror of 94%, a maximum laser power obtained 660 mW corresponding to laser efficiency of 30%.

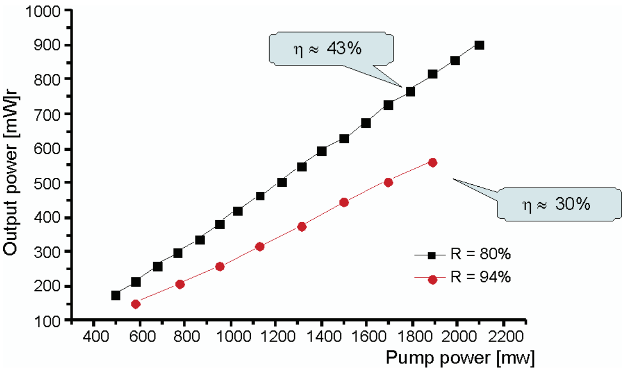

Fig. 4. Power characteristic of laser

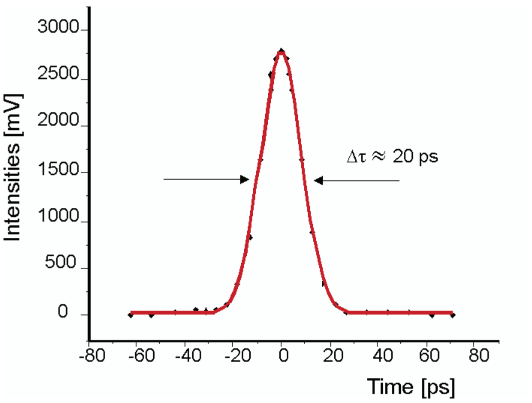

Fig. 5. Autocorrelation trace of laser pulse

The width of mode-locked laser pulse is measured by an autocorrelation system. The autocorrelation trace is shown in Fig. 5. Assuming that the pulse shape of laser is in form of Gaussian profile so we obtained the pulse width of mode-locking laser is about 12 ps.

II.2. Research and development a diode-pumped passively mode-locked $Nd:YVO_4$ laser operated at pulse repetition rates lower than 10 MHz

For applications, such as fluorescent lifetime measurement, the fluorescence lifetime of numerous organic molecules is in the range of a nanosecond to hundreds of picoseconds, short laser pulses of several tenths of picoseconds are ideally needed from reliable pump laser sources. The pulse repetition rate is of the pumping laser source used is also an important parameter in experiments: High repetition rates ensure fast acquisition of the fluorescence decay signal and allow the dynamic processes to be studied. If the repetition rate is too high and exceeds several megahertz, problems appear in the complex signal-processing devices during the acquisition of the data. Therefore, a pulse repetition rate less than 10 MHz seems to be a good requirement for this kind of application. However, for mode-locked solid state lasers with resonator design in Fig. 1, the repetition rate in the range of 30-100 MHz that determined entirely by their resonator length. To obtain a pulse repetition rate lower than 10 MHz, the resonator length should be larger than 15 m. To achieve such long resonator, one introduced a multiple-pass cavity (MPC) based on the classical Herriott-style MPC with two concave mirrors [5]. This resonator configuration was recently used successfully to decrease the frequency of a $Ti:Al_2O_3$ mode-locked laser to 4 MHz [6, 7]. The configuration of the MPC used in our system is in fact a version of the Herriott-style MPC folded in two with the help of two plane mirrors (Fig. 6). The distance of both concave mirrors (r = 2 m) from the two plane mirrors is fixed at approximately the focal length of the concave mirrors. The beam is periodically focused and defocused after each reflection on the concave and plane mirrors, respectively.

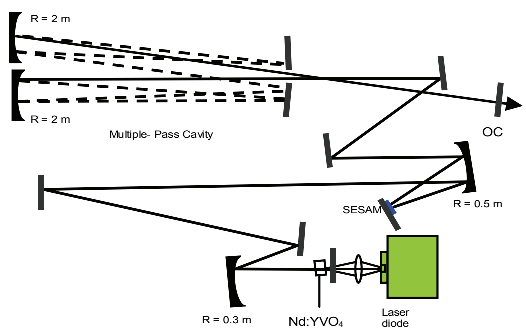

Fig. 6. Schematic of the long cavity diode-pumped passively mode-locked $Nd:YVO_4$ laser

During the alignment of the MPC inside the laser resonator, various lengths of the laser resonator could be used, resulting each time in the operation of the mode-locked laser system on a number of different repetition rates. The easiest for optics element arrange and control of the number of reflections inside the MPC is with 6 times reflection in MPC so we are archived with cavity length more than 15 m (corresponding repetition rate about 8.8 MHz). With the use of an output mirror of 20% and 6% transmission at 1064 nm, the laser provides the pulse duration of 12 ps (Fig. 8) and an average laser power of 410 mW, corresponding to about 4 kW peak power (Fig. 7).

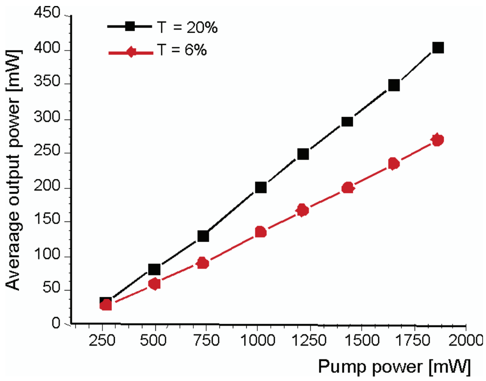

Fig. 7. Power characteristic of laser

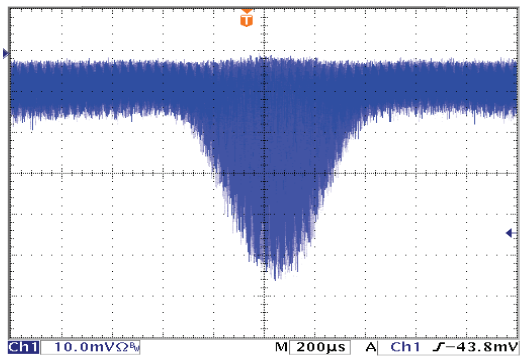

Fig. 8. Interference auto-correlation trace of pulse duration of 12 ps (assuming a Gaussian profile)

The pulse trains obtained from the mode-locked $Nd:YVO_4$ laser with a fast photodiode (rise time < 200ps) and a digital oscilloscope (Tektronix 1.5 GHz, 20 GS/s) was shown in Fig. 9.

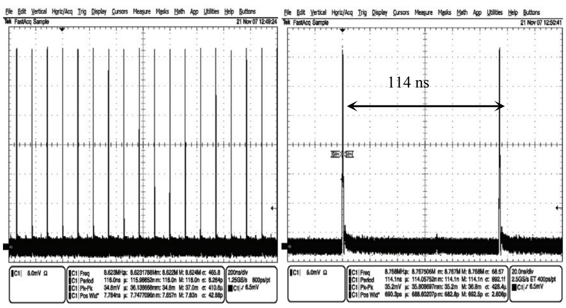

Fig. 9. presents a pulse train stable operation at repetition rate of 8.8 MHz or 114 ns of pulse separation

II.3. Laser amplification and wavelength conversion

For the amplifier (Fig. 10), we choose a $Nd:YVO_4$ crystal (1% doped $3 \times 3 \times 3$ mm^3) as a gain medium because of its high emission cross section, in order to have a good energy extraction. To decrease the thermal effects, the $Nd:YVO_4$ crystal was attached to copper blocks.

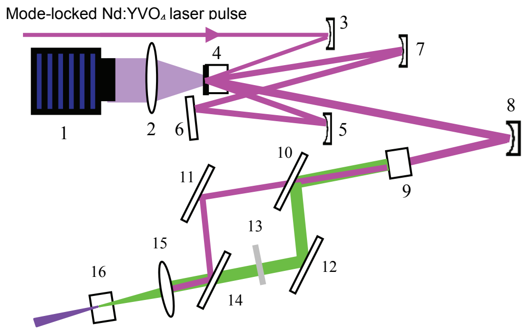

Fig. 10 Experimental setup for amplifier and converter wavelength of laser

Optical elements of system includes: (1) CW laser diode – (2) pump lens – (4) Nd: YVO_4 crystal – (3), (5-8), (10-12) and (14) mirrors – (9) KTP crystal – (13) 2-nd half wave plate – (15) lens, (16) 3rd frequency crystal

Average laser powers of 650 mW and 900 mW are then obtained with a 2-pass or 4-pass configuration, respectively (Fig. 11). Increased efficiency of the amplifier results from the pump of laser diode. However, the efficiency of the 4-pass amplifier is not as high as expected; this might be due to the thermal effects.

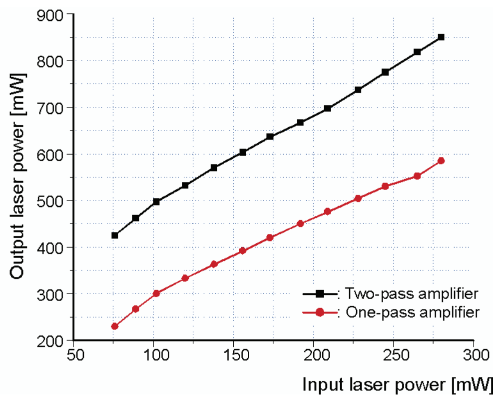

Fig. 11. Power characteristics of the two and four-pass laser amplifier

For the nonlinear processes, we first use a 5 mm long type I KTP crystal for second harmonic generation. The output green power at 532 nm is up to 130 mW with a pu-lse duration lightly shortened by non-linear conversion of around 10 ps (Fig. 12). For direct fourth generation, a 5 mm

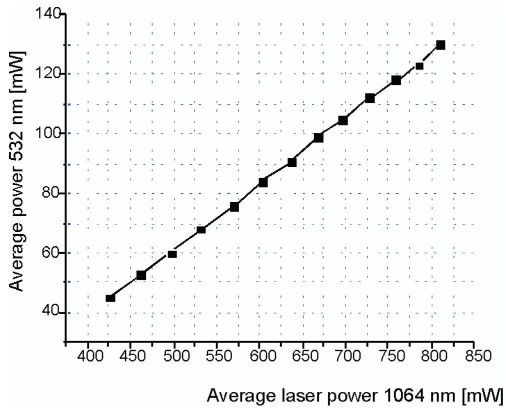

Fig. 12. Average power at 532 nm in function of input average power at 1064 nm

a 5 mm long BBO crystal was used to the second harmonic generation pulse at 532 nm, the output power at 266 nm could be up to 15 mW. For third harmonic generation, the IR and the green are then recombined in a second non-linear crystal (5 mm long type II KDP). An average power of 45 mW at 8.8 MHz with pulse duration of around 10 ps is obtained at 355 nm, corresponding to a conversion efficiency of 5% from IR to UV. It is noted that the non-linear conversion efficient is straightforward improved much better, due to the use of non-linear crystals and optical components given in our laboratory.

III. CONCLUSION

The research and development of a passively mode-locked diode-pumped $Nd:YVO_4$ laser operating at 1064 nm at pulse repetition rates in range of 30-100 MHz have been achieved. The mode-locking of the laser was obtained with a low-modulation semiconductor saturable absorber mirror (2%). In addition, a super long cavity with multiple-pass resonator configuration folded with two concave mirrors ($r = 2$ m) is achieved. We also have successfully developed an amplifier laser power and converter wavelength to visible and UV. As a result, the laser system was compact and well arranged on an optical table (L120 × W40 cm^2). Such a picoseconds laser source is demanded and very attractive for applications in biology and photonics.

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DO QUOC KHANH was born in Thanh Hoa, Vietnam, in 1976. He received the Bachelor degree in Physics from the National University of Hanoi, Vietnam in 1998 and Master degree in 2004 and PhD degree in 2009 in Laser Spectroscopy from the Institute of Physics, Vietnam Academy of Science and Technology (VAST). From 1998 to 2009 he was researcher in Institute of Physics, (VAST). His main research interests are focused on ultra-short laser sources and laser spectroscopy.

NGUYEN DAI HUNG was born in 1954 in Hanoi, Vietnam. He received the BS (1977) degree in Optics from Hanoi University of Science, Vietnam and in 1977 the PhD degree in optics and laser physics, Spectroscopy from the Institute of Physics Vietnam Academy of Science and Technology (VAST) in 1988. From 1988 to 1992, he was visitor researcher at Laboratoire de Photophysique Moleculaire in Paris University 11, France. From 1992 to 1996, he was Assoc. Professor in the Institute of Materials Science, Vietnam. From 1996 to 1997, he was Assoc. Professor in joint RIKEN Lab., Kyushu University, Japan. From 1998 to 2003, he was director of Center for Quantum Electronics and head of the Laboratory of Lasers and Photonics, Institute of Physics, VAST. From 2003, he was full Professor,Vice Director of Institute of Physics, VAST. Since 2007, he was Director of the Institute of Physics, VAST. His researches interests are focussed in Ultra-short pulse lasers and its applications.

PHAM LONG was born in Hanoi, Vietnam in 1960. He received Bachelor degree in Physics from the University of Hanoi in 1981 and PhD in Physics from Institute of Physics, Vietnam Academy of Science and Technology. He is permarnant researcher in the Institute of Physics. His area researches are Laser Physics and Technology: Fundamentals and Applications and specific topic of interest focused in new materials and technologies for ultrafast laser and its applications.

NGUYEN TRONG NGHIA received the BS degree in physics from National University of Hanoi, in 2002. From 2007 to 2009, he was Master student in laser – photonics at the Institute of Physics, Vietnamese Academy of Science & Technology (VAST), Hanoi – Vietnam.

TRINH DINH HUY was born in Hanoi, Vietnam, in 1983. He received the Bachelor degree at the Technology, University of Hanoi, Vietnam in 2005 and Master degree in 2009 in Laser Spectroscopy from the Institute of Physics, Vietnam Academy of Science and Technology (VAST). From 2005 to 2009 he was researcher at the Institute of Physics, (VAST). His main research interests are concentrated on solid-state laser, laser and fluorescence spectroscopy.