Contributed paper

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CW mode locked Nd:YVO_4 laser pumped by 20-W laser diode bar

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The efficient cw mode locking (cw-ML) regime was demonstrated in Nd:YVO_4 laser by means of saturable absorber mirror (SAM). The 0.3-at.% Nd^{3+} doped 10-mm-long YVO_4 crystal end pumped by 20- W diode module with a beam shaper was applied as a gain medium located in the close vicinity to the rear flat mirror of the first arm of Z-type resonator of 316 cm total length with two curved mirrors of 100-cm curvature radii. The SAM of 2%-saturable absorptance and saturation fluence of 50 μJ/cm^2 was mounted at the opposite end of a resonator. The developed "dynamically stable" cavity design mitigates detrimental role of thermal aberration in gain medium, enforcing clean perfect mode locking even for the highest pump densities. The cw-ML pulses with 47.5 MHz repetition rate and pulse durations in the range of 15–20 ps were observed for a wide range of pump powers and output coupler losses. In the best case, for 32% of output coupler transmission, up to 6.2 W of average power with near 35% slope efficiency was achieved. The thresholds for Q -switched ML, cw-ML regimes were 2.67 W and 6.13 W of pump power, respectively. For the maximum pump power of 20 W we obtained 133 nJ of pulse energy with 16-ps pulse duration, resulting in a peak power higher than 8 kW. The threshold energy density at SAM giving the QML regime was estimated to be about 30 μJ/cm^2, threshold of cw-ML regime was 220 μJ/cm^2.

Keywords: diode pumped lasers, mode locking, SESAM.

1. Introduction

The regime of mode locking requires the special optoelectronic elements or techniques providing longitudinal mode synchronization by means of active methods [1,2] based on phase or amplitude modulation with the frequency equal to reciprocity of cavity roundtrip time or passive ones [1–3]. Up to the 90'ies of the last century, cw mode locked lasers have been ones of the most cumbersome and complicated oscillators with active control of a cavity length, stabilization of modulation frequency, etc. Even applying passive methods (e.g., Kerr lens mode locking) the problems with self starting have not been eliminated. The invention of efficient semiconductor saturable absorbers (see Ref. 4), exploiting multilayer coatings and fast recovery time carriers "located" in quantum well stack, has become one of the important milestones in laser technology. Specially engineered for definite aims, optoelectronic elements based on such technology provide the construction of mode locked lasers operating at several wavelengths (0.6–2.5 μm) with the output powers of a few mW up to dozens Watts and frequencies of above 100 GHz [5]. From the principle of operation point of view, the semiconductor saturable absorbers can be divided into two groups: semiconductor saturable absorbing mirrors (SAM's) and semiconductor saturbale absorbing transmission filters (SATF's). In the first, the most widespread group, the reflectivity changes from some level (> 0.9) up to near 1, the saturable losses are of the range of a few percent, saturation fluence is of dozens up to a few hundreds of μJ/cm^2. Because of low damage thresholds, such elements can be applied to relatively low energy mode locked pulses (~1 μJ). The highest, to our knowledge, average power of 80 W was demonstrated for thin disk Yb:YAG laser with pulse energy of few parts of mJ [6]. The only competition for SAM's for higher power levels are nonlinear mirrors based on Stankov's concept [7,8]. The developed in last years new group of SATF's ensures mode locked regime even at the higher energy levels up to a few mJ [9,10]. For a wide range of application (microsurgery, chemistry, micro-machining etc), the ps pulses of moderate energy of a few tenth of μJ with MHz rep. rates are required. Such requirements can be fulfilled by diode pumped neodymium lasers operating at the output powers of dozens Watts. The aim of this work is examination of SAM's for such type lasers. The special type of cavity with relatively long roundtrip time (21 ns) providing the efficient exploitation of SAM, having 50 μJ/cm^2 saturation energy density, was presented in Sec. 2. In the next section, the investigation results of such a mode locked laser with SAM were presented. In the last section, the conclusions were drawn.

2. Design and analysis of laser cavity

We have chosen the Z-type resonator (shown in Fig. 1) as the most flexible scheme for our purposes. It is well known, that the mode size of diode pumped laser depends significantly on thermal lens power induced in a gain me-

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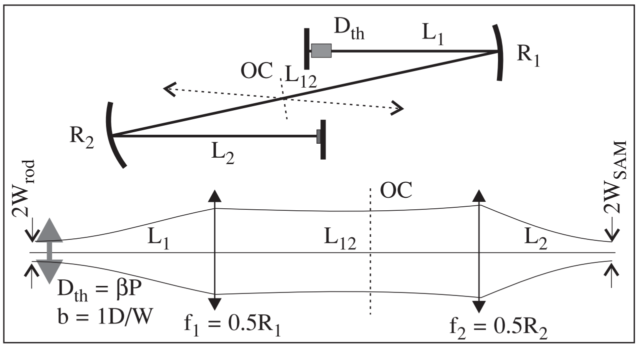


Fig. 1. Scheme of Z-type resonator: R_1, R_2 1-m curvature mirrors, L_1 = 515 mm, L_{12} = 2080 mm, L_3 = 549 mm, and D_{th} is the dioptric power of gain medium and OC is the partially transmitting output coupler.

dium. It was found in separate experiments that the available pump power range of 1–20 W approximately corresponds to the dioptric thermal lens power range of 1–20 D for mean pump beam width of 0.6 mm. Thus, we have started calculation of the cavity scheme, shown in Fig. 1, taking the above relation between pump power and thermal lens (see Fig. 2, dotted line). Moreover, to provide high mode matching efficiency, we have assumed that inside an active medium, a mode diameter should be not higher than 0.5 mm. At the opposite end of the resonator, the SAM element of 0.05 mJ/cm^2 saturation energy density has to be inserted. Assuming, that the generation starts with 2-W pump threshold and slope efficiency of 35% for output coupling losses of 30%, the internal power density incident at SAM can be calculated. Concluding, the following assumptions for the cavity design were defined:

- round trip time of approximately 20–21 ns,
- the input/output energetic characteristics of 0.35 slope, 1 D/W of thermal lens rate,
- energy density at SAM surface of 50 µJ/cm^2 near threshold (i.e., for 1–2 D of thermal lens),
- mode radius at active medium approximately constant and less than 0.25 mm for 1–20 D of a thermal lens.

Applying the numerical procedure implemented in MathCad 2001, we have found the parameters of cavity satisfying the above requirements. The developed "dynamically stable" layout of Z-type resonator provides near constant mode radius for the 1st cavity arm with slightly diminishing mode radius in the 2nd arm with increase in pump power (see Fig. 2). The mode area at SAM plane, inversely proportional to pump power, gives nonlinear ("quadratic") dependence of energy density on pump power (see Fig. 3). The 50 µJ/cm^2 value of energy density corresponds to pump power of 3.3 W. For available maximal pump power of 20 W, the estimated internal energy density is 2.4 mJ/cm^2, corresponding to 240 MW/cm^2 for 10-ps mode locked pulses. This is far below of SAM damage threshold of 800 MW/cm^2. The effective power density at SAM should be much lower as a result of increase in a beam volume with pump power and not perfect mode locking.

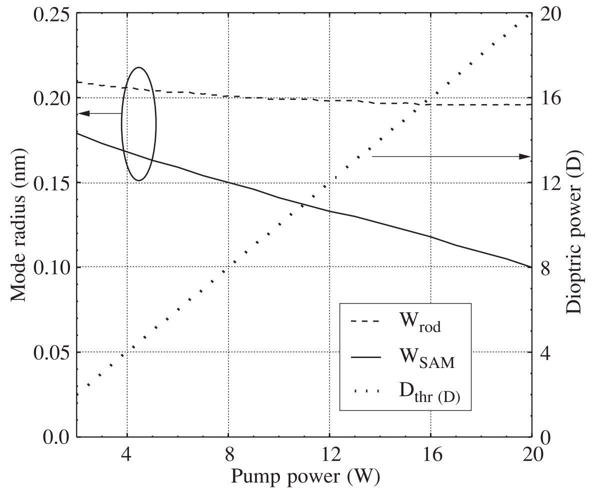


Fig. 2. Mode radii at rod (dashed), at SAM (continuous), dioptric power (dotted) *vs*. pump power.

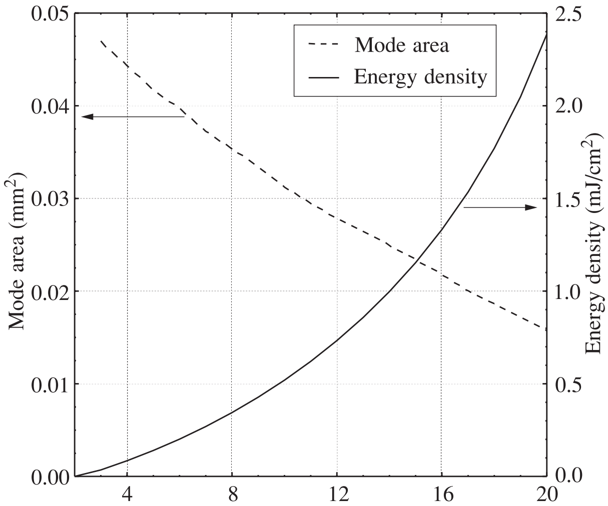


Fig. 3. Energy density, mode area at SAM surface *vs*. pump power.

3. Investigations of mode locked regime

The investigations of mode locked regime were carried out in the laser set up shown in Fig. 4. The SAM element made by BATOP Optoelectronics (its parameters are presented in Table 1) was used in experiments.

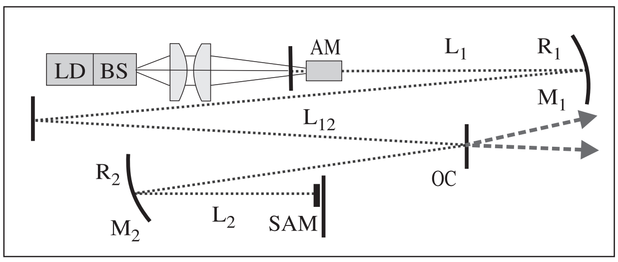


Fig. 4. Scheme of mode locked laser set up: R_1 and R_2 are 1-m curvature mirrors, SAM – semiconductor saturable mirror, AM – gain medium 0.3% Nd:YVO$_4$ 3×3×10 mm^3, LDBS- 20-W laser diode bar with a beam shaper, L_1 = 515 mm, L_{12} = 2080 mm, L_3 = 549 mm, OC-flat output coupler of T_{OC} = 0.161, for both bounces 0.296.

Table 1. Parameters of SAM.

Wavelength (nm)	λ = 1064 nm
High reflection band (R > 99%)	λ = 1030–1100 nm
Saturation fluence	Φ_{sat} = 50 µJ/cm^2
Saturable absorptance	A_0 = 2%
Non saturable loss	ΔA_{ns} < 0.3%
Damage threshold for 10-ps pulses	I_{dam} = 800 MW/cm^2
Relaxation time constant	10 ps
Working area	4×4 mm^2

3.1. Investigations of energetic characteristics

The parameters of cavity, determined in numerical analysis, were verified in experiments. Changing L_2 and L_{12}, we have found the configuration providing the best mode matching and output efficiency. Further, we have found experimentally the optimum value of output coupler losses (see Fig. 5). As it was shown in Fig. 6, the highest output power was achieved for the output coupler of T_{oc} = 0.161 giving double pass outcoupling loss of 29.6%. For such a laser configuration the resonator frequency was 47.5 MHz. The CW generation started at pump power of 1.2 W. The maximum mean output power of 6.2 W and 133-nJ output pulse energy was demonstrated corresponding to 2.41 mJ/cm^2 of energy density at SAM.

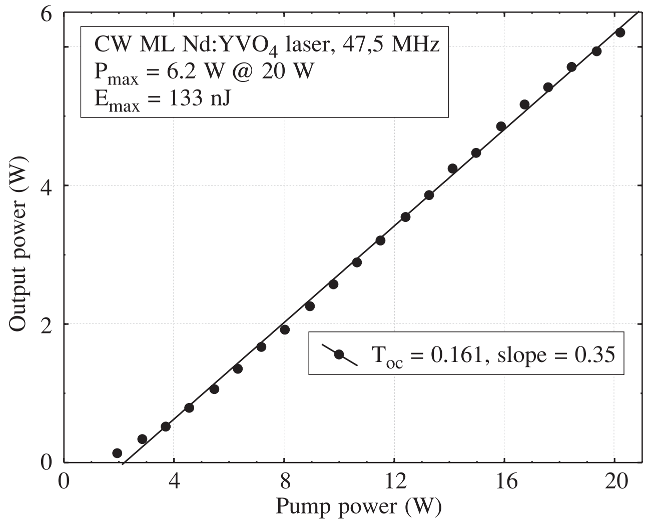


Fig. 6. Output power *vs*. pump power for the best case.

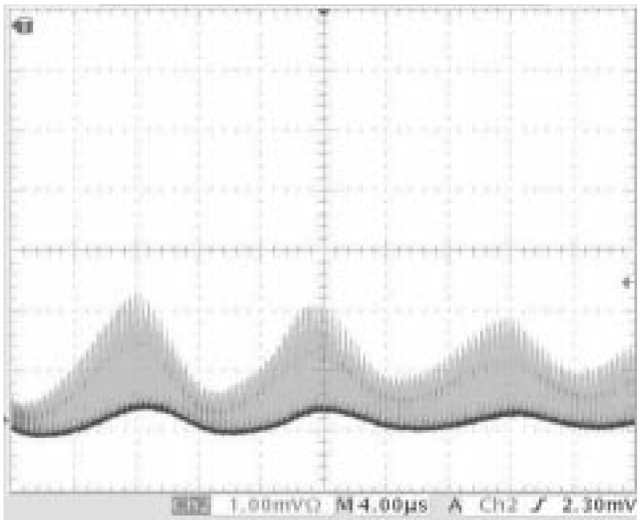


Fig. 7. Q-switched mode locked pulses for 5-W pump.

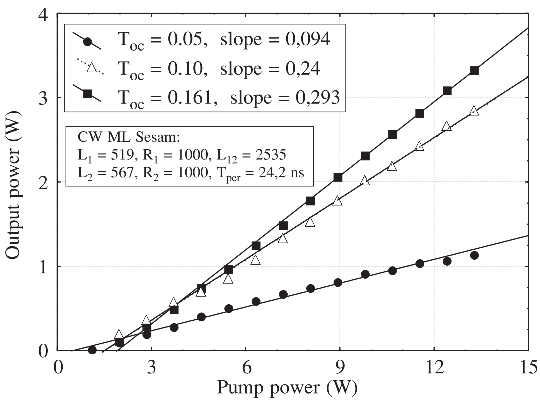


Fig. 5. Output power *vs*. pump power for different OC losses.

3.2. Investigations of temporal characteristics

For electronic detection, the photo-receiver based on InGaAs photodiode FGA04 of 0.1-ns rise time was applied. The signal from a photoreceiver was sent to 500-MHz Tektronix TDS3052 digital oscilloscope [see Figs. 7, 8, and Fig. 9(b)] or 1-GHz DSA601 oscilloscope [Fig. 9(a)]. The start of Q-switched mode locking regime (see Fig. 7) was observed for pump power of 2.7 W corresponding to 30 µJ/cm^2 energy density at SAM. The stable cw mode locking [see Figs. 8, 9(a), and 9(b)] has begun at pump power of 6.13 W corre-

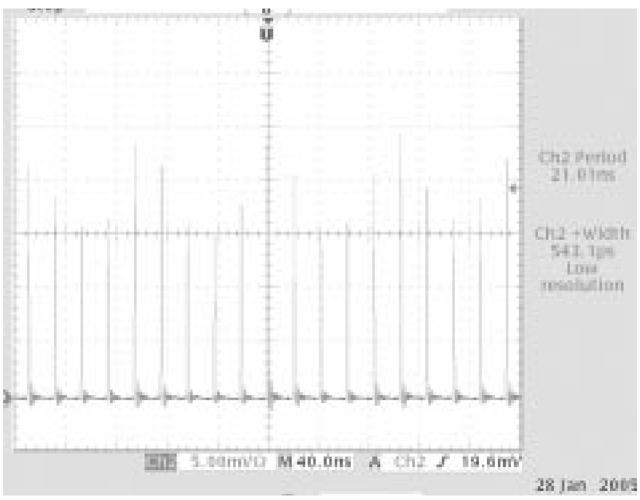
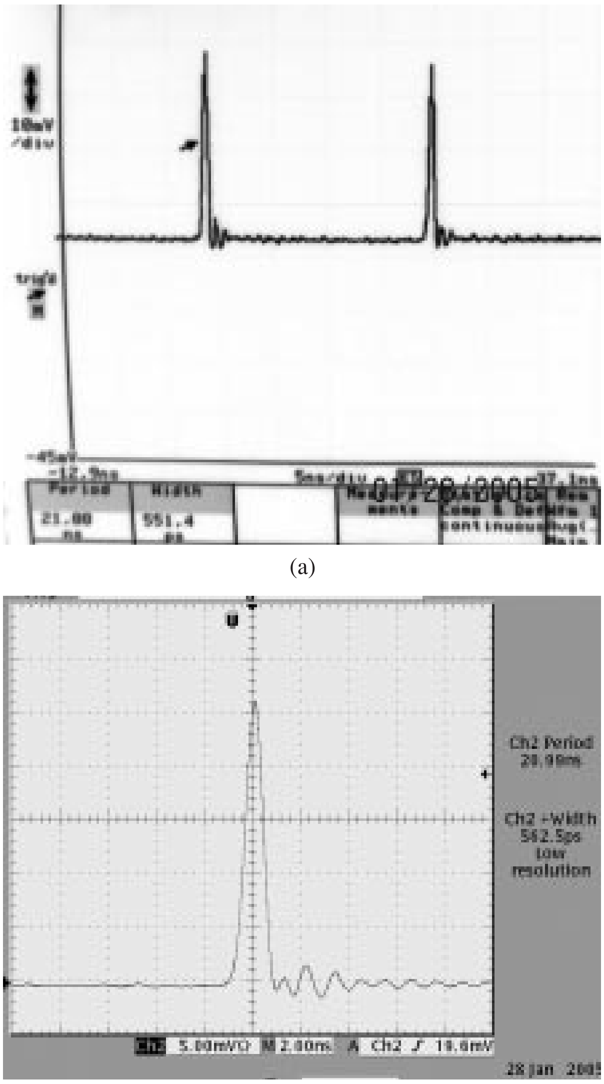


Fig. 8. CW-switched mode locked pulses for 15-W pump power.



(a)

(b)

Fig. 9. CW mode locked pulses registered with 1-GHz oscilloscope (a), CW mode locked pulse registered with 500-MHz oscilloscope (b).

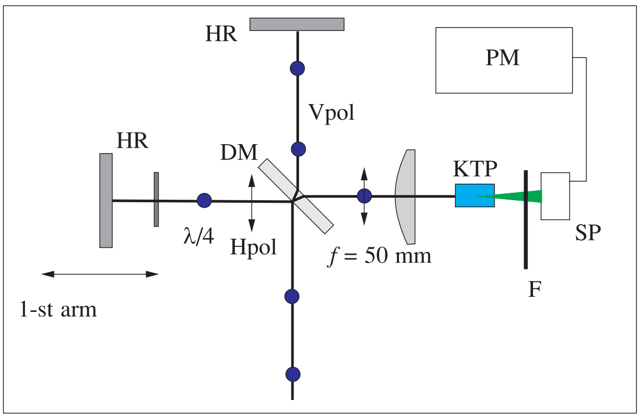


Fig. 10. Scheme of auto-correlator set up: HR- highly reflective at 1064 nm mirror, λ/4-quarter-wave plate, DM – partially transmitting mirror, F – filter with > 99% loss for 1064 nm, SP-818 SL probe, PM – power meter Newport 1825, and *f* – lens of 50-mm focal length.

sponding to 220 μJ/cm^2 energy density at SAM. The fully modulated mode locked pulse trains were observed as a rule, with slightly modulated (in the range of 10%) amplitude (see Fig. 8). The residual oscillations [see Fig. 9(a), and 9(b)] after the main pulse were caused by electronic limitations of photo-receiver and scopes.

For measurement of pulse durations, the auto-correlator in Michelson scheme with polarization rotation in the 1st arm was arranged (see Fig. 10). The output signal from Michelson set up was focused inside II type KTP crystal (3×3×5 mm^3) for II harmonic conversion and measured after "cut off" fundamental wavelength with power meter equipped with a semiconductor probe of 1-ms rise time. The typical correlogram was shown in Fig. 11. Assuming FWHM criterion and sech^2(t/τ_s) shape, the pulse duration τ_s was equal to 15.9 ps for experimental data shown in Fig. 11. The typical values of pulse durations were in the range of 15–20 ps. Some kind of multi pulsing (double and triple pulses) were observed as well.

4. Conclusions

The developed "dynamically stable" cavity of mode locked laser provides the proper size of mode in gain medium and at SAM surface, resulting in cw mode locking regime for wide range of thermal lens power induced in a gain medium. The cw-ML pulses with 47.5 MHz repetition rate and durations in the range of 15–20 ps were observed for wide range output coupler losses and pump powers. The thresholds for Q-switched mode locking and cw-mode locking regimes were 2.67 W and 6.13 W of pump power, respectively. The threshold energy density at SAM giving the QML regime was estimated to be about 30 μJ/cm^2, threshold of cw-ML regime was 220 μJ/cm^2. In the best case for 30% of outcoupling losses, up to 6.2 W of average

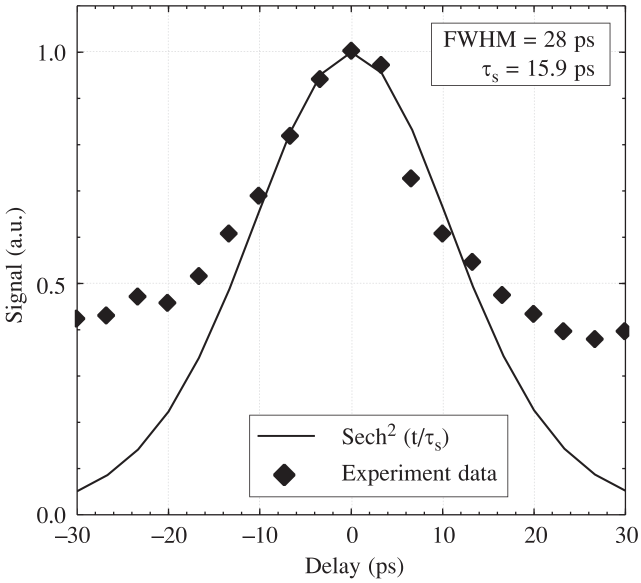


Fig. 11. II harmonic signal data from auto-correlator (diamonds), sech^2(t/τ_s) fitting (continuous) *vs.* delay time.

power with near 35% slope efficiency was achieved. For the maximal pump power of 20 W we obtained 133 nJ of pulse energy with 16-ps pulse duration, resulting in peak power higher than 8 kW. Relatively long (comparing to 240 GHz gain bandwidth of vanadate) pulses evidence the imperfection of mode locking, which in principle, can be eliminated.

Acknowledgments

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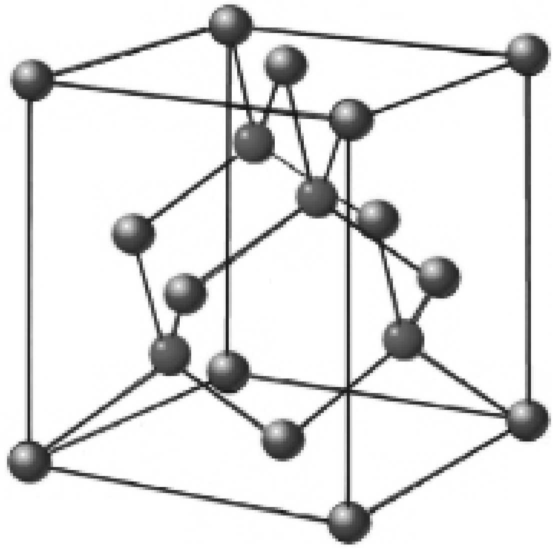

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