CHINESE OPTICS LETTERS
Vol. 21, No. 3 | March 2023

Subharmonic mode locking of a Q-switched Nd:YAG laser

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Received August 29, 2022 | Accepted October 13, 2022 | Posted Online November 8, 2022

A *Q*-switched Nd:YAG laser has been actively mode-locked at a subharmonic frequency for the first time, to the authors' knowledge. The laser operation mode is provided by a combination of a traveling wave acousto-optic modulator and a spherical cavity mirror. The dynamics of laser generation is investigated. Pulses with a duration of 70 ps and a peak power of about 10 MW were obtained. Also presented are new results on obtaining high-power (∼60 kW) picosecond tunable radiation in the ∼620 nm region based on frequency conversion of a superluminescent parametric generator pumped by such a laser.

Keywords: Nd:YAG laser; diode pumping; *Q* switching; mode locking; parametric light generators.
DOI: 10.3788/COL202321.031406

1. Introduction

Obtaining a high peak output power from a CW diode-pumped solid-state laser is important for applications such as nonlinear optics, high-precision material processing, Raman spectroscopy, and other uses. In Refs. [1–3], a method was proposed that allows using one traveling wave acousto-optic modulator (AOM) and an end spherical mirror (SM) of the cavity (SMAOM method) to simultaneously obtain mode locking and *Q* switching (QML) in solid-state lasers. In Ref. [4], an "autoQML regime" was discovered in which *Q* switching occurs at the frequency of relaxation oscillations of the laser. The SMAOM method is investigated theoretically by the authors[5,6]. Depending on the settings of the parameters, a laser with the SMAOM method can operate in one of the following regimes: continuous wave generation, *Q* switching, mode locking, autoQML, and QML modes. The method makes it possible to create a laser design that provides compactness, simplicity, and a relatively low cost of manufacturing the device, and the peak powers attainable allow efficient nonlinear conversion of the radiation frequency outside the cavity, including optical parametric generator (OPG) in the superluminescence mode. In particular, coherent anti-Stokes Raman scattering spectroscopy applications require tunable radiation in the 620 nm region.

In a laser with the SMAOM method, mode locking occurs due to the return of one of the beams diffracted by the AOM back into the laser cavity. Returning to the cavity, this beam receives a frequency addition equal to twice the ultrasonic wave frequency $2f$. If the condition $c/2L = 2f$ is satisfied, then mode locking occurs. The second diffracted beam leaving the resonator introduces losses; by varying them, the *Q*-switching mode is implemented. Modulating radiation with a frequency equal to the laser intermode spacing or shifting its frequency by this amount is a standard solution for laser mode locking. A solution is also known in which radiation modulation occurs at multiple harmonics, in which case the pulse repetition rate increases with the same multiplicity[7]. Radiation modulation can also be performed at subharmonic frequencies. The authors of Refs. [8,9] succeeded in achieving mode locking in ring fiber lasers operating at various subharmonics using amplitude modulation of the radiation. In this case, the laser operated in a quasi-QML mode with a train frequency equal to the subharmonic frequency. Modulation at the subharmonic frequency is also used in semiconductor lasers with synchronous and hybrid mode locking[10,11]. In such lasers, modulation of the amplitude of the generated pulses can be observed at the resonant frequencies, especially if this frequency is close to the frequency of relaxation oscillations of the laser[11]. Mode locking at subharmonic frequencies is also known in radio physics, for example, in synchronous oscillators[12], and oscillators based on Gunn diodes[13] and impact ionization avalanche transit-time (IMPATT) diodes[14]. Subharmonic mode locking was not used in "classical" solid-state lasers, although it is of considerable interest. It allows avoiding the exact equality of the resonator length (intermode interval) and the AOM carrier frequency, reducing the cavity size and creating much more compact laser designs, while using the advantages of active mode locking, such as the stability of the output radiation parameters. Compactness, cost, and stability of output characteristics are important factors influencing the competitiveness of laser systems. In addition, the phenomenon of mode locking at subharmonic frequencies can explain the appearance of mode locking in lasers with an AOM, the operating frequency of which is much lower than the intermode interval of the laser (see, for example, Ref. [15]).

In the present work, mode locking by a second-order subharmonic in a diode-pumped Nd:YAG laser with the SMAOM method is studied. Mode locking is achieved by returning a diffracted beam to the resonator; the frequency of such a beam is shifted by half the intermode interval of the resonator using an acousto-optic traveling wave modulator. The dynamics of laser generation is studied, and laser generation is obtained in the QML and autoQML modes. Also, the results on the use of this laser for obtaining ultrashort pulses with a tunable frequency in the near-IR, mid-IR and in the visible range are presented.

2. Experiment Setup

The experimental scheme of the laser is shown in Fig. 1. The active element was a Nd:YAG crystal 2 mm in diameter and 65 mm in length with diode side pumping at a wavelength of 808 nm. The radii of curvature of the spherical mirrors M1 and M2 were 0.5 and 0.3 m, respectively, and their reflection coefficients at the operating wavelength $\lambda = 1064\,\text{nm}$ were >99.5% and 86%, respectively. Two fused silica Brewster plates were used as a polarizer. The optical length of the cavity was $L \approx 75\,\text{cm}$. The AOM with antireflection ends (model MZ-322) was located at the Bragg angle to the optical axis of the cavity next to mirror M2. The optical path length between the reflecting surface of the mirror M2 and the center of the modulator was equal to the radius of curvature of mirror M2. An operating frequency f = 50,049.6 kHz, equal to a quarter of the intermode interval ($c/2L = 4f$), was supplied to the AOM piezoelectric transducer. In this case, after a double passage of radiation through the AOM, the diffracted beam 1 (see Fig. 1) will partially return to the resonator with an addition to the frequency equal to $2f$, i.e., the radiation will be frequency-shifted by half the intermode interval. After this beam again passes through the AOM twice after the next complete round trip of the resonator, its frequency will be shifted by $4f$, which will correspond to the intermode interval. Thus, laser mode locking will occur.

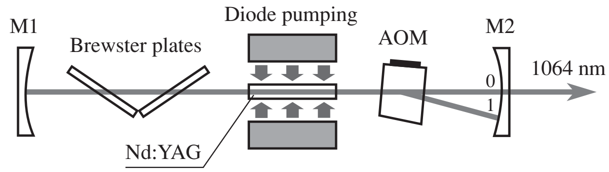

Fig. 1. Laser circuit. M1 and M2, cavity mirrors; AOM, acousto-optic modulator; Nd:YAG, active element; 0, zeroth-order diffraction beam; 1, first-order diffraction beam.

3. Experimental Results

As in previous works[3,16,17], the resonator length was tuned when a continuous ultrasonic frequency signal was applied to the modulator by moving one of the resonator mirrors to achieve stable mode locking in continuous mode (CWML). The diffraction efficiency of the AOM was determined by measuring the power of zeroth-order and first-order diffraction beams emerging from the resonator through mirror M2 and was $k_d = 7\%$. The coefficient k_d is the fraction of the light field reflected from the acoustic wave in the AOM. In this case, significant pulsations were present in the pulse amplitude. Therefore, the optimal resonator length was considered to be the one at which the pulsations were minimal and amounted to approximately ±20%, while complete mode locking was observed. Figure 2(a) shows the oscillogram corresponding to this mode. As was demonstrated earlier[3,17], the autoQML mode can be obtained by varying both the resonator length and the coefficient k_d. Changing one or another parameter leads to the transition of the indicated pulsations to the autoQML generation mode. The process of the emergence of a self-oscillatory regime is explained in detail theoretically in Refs. [5,6]. A stable autoQML mode was observed within the cavity length detuning $|\Delta L| = 60$–$110\,\mu\text{m}$, both with the increasing and decreasing cavity length [see Fig. 2(b)]. The pulse train frequency was about 50 kHz, and the average output power was ≈6.5 W. At $\Delta L = 0$, the autoQML mode with a pulse train frequency of 45 kHz was obtained by increasing k_d to 21%, while the output

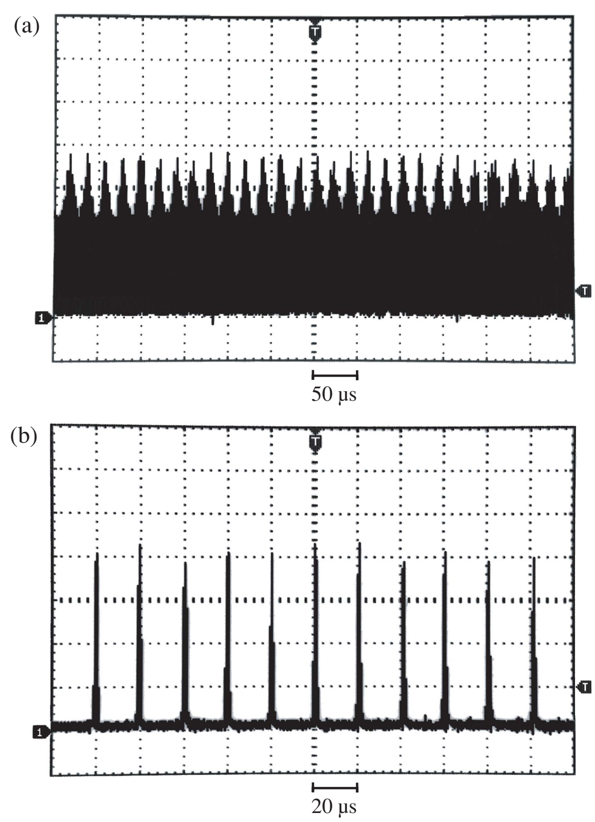

Fig. 2. Oscillograms of the output laser radiation at $k_d \approx 7\%$. (a) $\Delta L = 0$, (b) $\Delta L = 80\,\mu\text{m}$.

power was ≈4.9 W. The coefficient k_d was varied by adjusting the power of the electrical signal supplied to the AOM piezoelectric transducer.

The QML generation mode was carried out at $k_d = 30\%$ by periodically turning off the audio signal with a frequency of $f_Q = 1$ kHz. The value of k_d was chosen experimentally to achieve the maximum peak laser power. At $k_d < 30\%$, significant prelase was observed before each Q-switch train due to insufficient AOM efficiency. For $k_d > 30\%$, a decrease in the average laser output power was observed. Both of these factors lead to a drop in the peak power of the laser. The oscillogram of a Q-switch pulse with mode locking is shown in Fig. 3. Such a Q-switch train contains (at half-maximum) 11 mode-locking pulses following at a frequency of 200 MHz.

The pulse duration was measured using an optical intensity autocorrelator, assembled according to a noncollinear phase-matching scheme in a KTP crystal with a thickness of 200 μm. The second-harmonic signal was recorded by a photodiode with slow response time, which ensured the averaging of the output signal of the autocorrelator. The measurement result is shown in Fig. 4. The form of the autocorrelation function corresponded to the form of the Lorentz function. The pulse duration was $\tau = 70$ ps. The absence of background and broadening of the edges (violations of the Bell shape) in the autocorrelation function indicates good mode locking. The average output power in the QML generation mode was $P_{AVE} = 4$ W. The pump power in all experiments was constant and amounted to 58 W. The peak power of pulses at the maximum of the Q-switch envelope can be defined as $2P_{AVE}/f_Q N\tau$, where N is the number of pulses at half-height of the Q-switch train ($N = 11$), and 2 is the multiplier for determining the power of the pulse with the maximum amplitude (at the maximum of the Q-switch envelope). Thus, the peak power was 10.4 MW, while the beam quality was $M^2 \approx 2$.

A series of preliminary experiments on mode locking in this laser using subharmonics of the third and fourth orders were carried out. This was realized by shortening the resonator length to 50 cm and 37.5 cm, respectively, while the AOM still operated at $f = 50{,}049.6$ kHz. In both cases, complete mode locking and laser generation in the QML regime were obtained, but the output characteristics have not yet been measured.

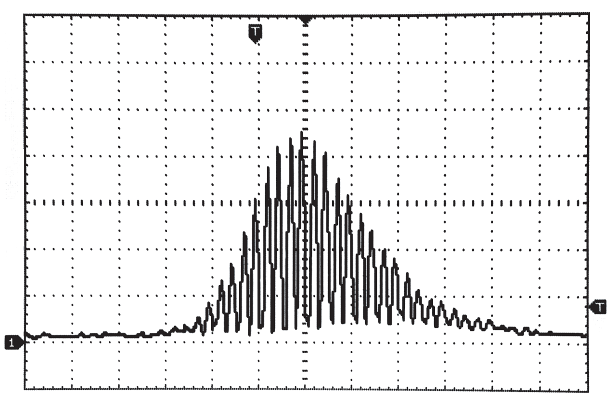

Fig. 3. Oscillogram of a lasing pulse at a wavelength of 1.064 μm in QML mode. The division along the abscissa axis is 20 ns.

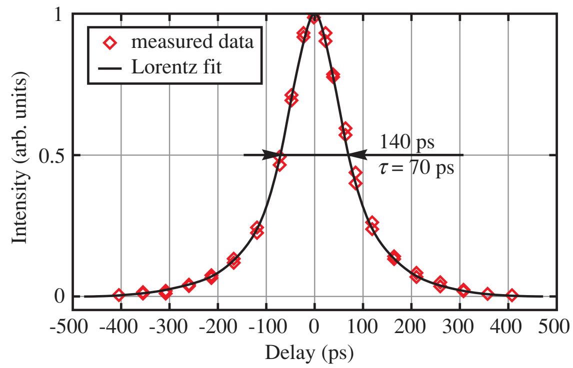

Fig. 4. Autocorrelation function in QML generation mode.

4. Cascade Conversion of Laser Radiation to the Region of 620 nm

The radiation shown in the Fig. 1 laser in the QML mode with a train frequency of 5 kHz was used to pump a superluminescent parametric generator and then convert its frequency to the visible region of the spectrum [cascade mixing of its signal wave (1475 nm) with a pump wave (1064 nm) for obtaining tunable radiation in the 620 nm region]. Figure 5 shows a diagram of the experimental setup. The characteristics of this scheme related to obtaining superluminescent parametric generation on a lithium niobate crystal with a periodic domain structure (PPLN) are described in detail in Ref. [18]. In this work, the same experimental results were obtained: the conversion efficiency was 83% for absorbed pump power.

The diameter of the pump radiation waist in the PPLN crystal was 160 μm. At a power incident on the PPLN crystal of 420 mW, the OPG output power was ~45 mW for idler

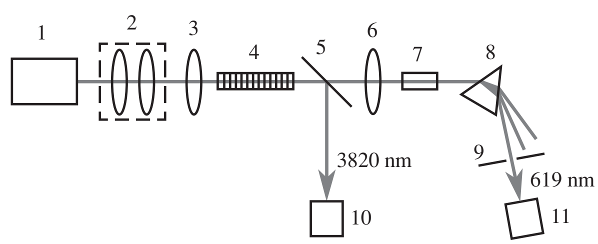

Fig. 5. Schematic of a setup for obtaining superluminescent generation tunable in the 620 nm region. 1, Nd:YAG pump laser; 2, collimator; 3, focusing lens; 4, PPLN crystal (50 mm length, polarization period 29.5 μm, ee-e phase synchronism); 5, selective mirror (HR at 3200–3850 nm, HT at 1050–1700 nm); 6, focusing lens; 7, LBO crystal (15 mm length, $\Theta = 90°$, $\varphi = 0°$, ee-o synchronism); 8, prism (TF10); 9, diaphragm; 10 and 11, measuring equipment.

wavelength ($\lambda = 3820\,\text{nm}$) and 140 mW for signal ($\lambda = 1475\,\text{nm}$). Approximately half of the pump power ($\lambda = 1064\,\text{nm}$) remained unconverted and came out of the PPLN crystal. Because the time delay of the pump and signal pulses is $l\Delta n/c \sim 1.7\,\text{ps}$ (where l is the length of the PPLN crystal, Δn is the difference in refractive indices at 1064 nm and in the region of 1475 nm, c is the speed of light) and it is much shorter than the duration of these pulses, and their divergences are equal[18]; then, further frequency conversion in an additional nonlinear element to the 620 nm region is possible. For this purpose, a lens 6 with a focal length of 5 cm, a nonlinear LBO crystal 7, a prism 8, and a diaphragm 9 were introduced to separate radiation at wavelengths 620, 1064, and 1475 nm, as well as measuring equipment 10 and 11 (Ophir power meter, MDR-23 monochromator or Michelson interferometer). To mix the signal wave and the pump wave, we used the ee-o synchronism of a nonlinear LBO crystal, since these waves have coinciding linear polarizations. In this case, the phase-matching angles are (for 1475 and 1064 nm) $\Theta = 88.3°$ and $\varphi = 0°$ at 20°C, which is close to noncritical phase matching. Under these conditions, the spectral and angular phase matching widths of a 15 mm LBO crystal are calculated to be more than 6 THz and about 40 mrad, respectively, which is greater than the widths of the lines involved in mixing (250 GHz for 1064 nm and 300 GHz for 1475 nm) and more than their divergences (30 mrad).

The average radiation power at a wavelength of 620 nm was 5 mW. The pulse duration was measured using a first-order autocorrelation function, which is the dependence of the visibility of the interference fringes on the difference in the path of the rays in the Michelson interferometer and gives the same results as nonlinear measurements[19]. The pulse duration was ≈5 ps, and the peak radiation power at the maximum of the Q-switch envelope was ≈57 kW. The resulting shortening of the pulse duration compared to pump laser pulses, coupled with a relatively low power, indicates the threshold nature of generation in this nonlinear process[20].

5. Conclusions

A diode-pumped Nd:YAG laser with the SMAOM method of mode locking, operating in the mode-locked and Q-switched mode was studied. In this case, mode locking is carried out at the subharmonic frequency. Various modes of laser generation, including the QML and autoQML modes, have been studied. In CWML mode, full mode locking was observed; after optimizing the cavity length, there were pulsations in the amplitude of ultrashort pulses of ~20% with a frequency of laser relaxation oscillations (45 kHz). The autocorrelation method was used to measure the duration of the output radiation pulses in the QML mode. At an average output power of 4 W, pulses with a duration of 70 ps and a peak power of about 10 MW were obtained. The use of mode locking at subharmonic frequencies allows for more compact laser designs without the need to replace or upgrade existing equipment. This laser was used to create a tunable radiation source in the region of ~620 nm with a pulse duration of 5 ps and a peak radiation power of ≈57 kW based on cascade frequency conversion of a superluminescent mid-IR parametric generator.

Acknowledgement

The authors would like to thank Vladimir Dmitrievich Ugozhaev for useful discussions and assistance in preparing the paper. This work was supported by the Russian Foundation for Basic Research and the Government of the Novosibirsk Region (No. 19-42-543002).

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