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二极管泵浦的被动调Q与脉冲幅度混沌 Nd：$LaMgAl_{11}O_{19}$全固态激光器

高子叶[1,2]，夏光琼[1]，邓涛[1]，林晓东[1]，唐曦[1]，樊利[1]，吴正茂[1,2]
（1 西南大学 物理科学与技术学院，重庆 400715）
（2 西南大学 数学与统计学院，重庆 400715）

摘 要：基于二极管泵浦Nd：$LaMgAl_{11}O_{19}$无序晶体激光器实现了被动调Q激光以及脉冲幅度混沌激光的输出。当泵浦功率在4.8～8.6 W范围内时，激光器运转在被动调Q状态；当泵浦功率为8.6 W时，调Q激光的平均输出功率为613 mW、重复频率为157.1 kHz、脉冲宽度为2.2 μs。当泵浦功率增加到8.7～10.5 W范围内时，输出激光的脉冲幅度呈不规则随机分布现象；通过分析脉冲峰值序列的自相关曲线、相位图、功率谱、随机直方图，判定激光器运转在脉冲幅度混沌状态；当泵浦功率功率为10.5 W时，脉冲幅度混沌激光的平均输出功率为814 mW。

关键词：被动调Q；脉冲幅度混沌；Nd：$LaMgAl_{11}O_{19}$无序晶体；二极管泵浦；全固态激光器
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Passively Q-switched and Pulse Amplitude Chaos Operations of a Diode-pumped Solid-state Nd：$LaMgAl_{11}O_{19}$ Laser

GAO Ziye[1,2]，XIA Guangqiong[1]，DENG Tao[1]，LIN Xiaodong[1]，TANG Xi[1]，FAN Li[1]，WU Zhengmao[1,2]
（1 *School of Physical Science and Technology*，*Southwest University*，*Chongqing* 400715，*China*）
（2 *School of Mathematics and Statistics*，*Southwest University*，*Chongqing* 400715，*China*）

Abstract：A passively Q-switched state or a pulse amplitude chaos output state are experimentally realized based on a diode-pumped Nd：$LaMgAl_{11}O_{19}$ disorder crystal laser. Experimental results indicate that when the pump power is in the range of 4.8～8.6 W，the Nd：LMA laser operates at a Q-switched state. For a pump power of 8.6 W，the average output power，repetition frequency，pulse width are about 613 mW，157.1 kHz，and 2.2 μs，respectively. When the pump power is in the range of 8.7～10.5 W，the pulse amplitudes of the Nd：LMA laser present irregular and random distributions，which are judged as chaos through analyzing the autocorrelation curve，phase portrait，power spectrum，and stochastic histogram of the pulse-peak time series. For a pump power of 10.5 W，the average output power arrives at about 814 mW.

Key words：Passively Q-switched；Pulse amplitude chaos；Nd：$LaMgAl_{11}O_{19}$ disorder crystal；Diode-

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First author：GAO Ziye（1985－），female，Ph. D. degree，mainly focuses on all-solid-state ultrafast lasers. Email：zygao@swu.edu.cn
Supervisor（**Contact author**）：WU Zhengmao（1970－），male，professor，Ph. D. degree，mainly focuses on nonlinear dynamics of semiconductor lasers. Email：zmwu@swu.edu.cn

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0 Introduction

Due to numerous advantages, such as compact structure, low cost, high efficiency, high pulse peak power, high pulse repetition, and good beam quality, Diode-Pumped Solid-State (DPSS) passively Q-switched lasers have been widely used in industrial, military, medical, and scientific research fields[1-3]. As is well known, for a DPSS passively Q-switched laser, saturable absorber and laser gain material are two important factors. For saturable absorber, since a Semiconductor Saturable Absorber Mirror (SESAM) is invented by KELLER U, it has been widely used as a saturable absorber to generate laser pulses[4-5]. For laser gain material, owing to lots of advantages including long lifetime, relatively large emission cross-section and large thermal conductivity, Nd^{3+}-doped laser materials, whether glass, ordered crystal or ceramic, such as Nd: glass (glass)[6], Nd:KGW ordered crystal[7], Nd: YAG ordered crystal[8], and Nd: LuAG ceramic[9], etc., have been successfully proven as laser gain media to produce Q-switched laser pulse. In addition to above Nd^{3+}-doped laser materials, Nd^{3+}-doped disordered crystals[10-11] have also attracted a great deal of attention because of their disordered structure, which makes them occupy the advantages of both glass and ordered crystal. In the 1980s, the laser characteristics based on Nd: $LaMgAl_{11}O_{19}$ (Nd: LMA) disordered crystals have been studied abroad[12-14], indicating that Nd:LMA disordered crystal is a potential laser gain medium. Meanwhile, domestic researchers have also carried out laser experiments based on Nd:LMA disordered crystal. In 1992, ZHANG Xiurong et al. reported a lamp-pumped Nd: LMA laser operating at 1 054 nm[15]. Then a diode-pumped Continuous-Wave (CW) Nd: LMA laser operating at 1 054 nm with an output power of 25 mW was demonstrate [16]. YANG Hongru et al. reported diode-pumped CW Nd:LMA lasers operating at 1 054 nm or 1 083 nm, where output powers can reach several hundred milliwatts [17-18]. In 1998, by additive-pulse mode-locking or Kerr-lens mode-locking, diode-pumped mode-locked Nd:LMA lasers were achieved[19-20]. Recently PAN Yuxin et al. demonstrated that watt-level CW laser based on a Nd: LMA disordered crystal, which is grown by the Czochralski method[21]. WANG Jiawei et al. reported a watt-level DPSS passively Q-switched Nd:LMA laser by adopting a Cr:YAG saturable absorber as a Q-switched device [22].

The pulsed lasers described above generally refer to pulsed lasers having a stable pulse amplitude, which are called stable pulsed lasers, and there have been many studies on stable pulsed lasers. In fact, there have been another type of pulsed lasers, Pulse Amplitude Chaos (PAC) lasers [23-24], whose pulse amplitude is random and has the characteristics of the chaotic laser. Due to its characteristics of the continuous frequency spectrum, noise-like, unpredictability, etc., the chaotic laser has been applied in many areas, such as chaotic communication[25-26], chaotic laser radar[27], random number generation[28-29], and reservoir computing[30-31]. At present, the chaotic laser is mainly generated from Semiconductor Lasers (SLs) by using different external perturbations, such as optical injection, optical feedback, photoelectric feedback, etc. [32-36]. Based on three-cascaded semiconductor lasers with optical injection, a chaotic laser with a bandwidth 35.2 GHz and the flatness of 5.6 dB was demonstrated[37]. BOUCHEZ G et al. reported the generation of chaotic laser with a bandwidth of 18 GHz based on a SL with optical phase-conjugate feedback[38]. By using a mutual optical injection structure with two distributed feedback lasers, a chaos laser with a bandwidth of 50 GHz and a flatness of 5.6 dB was realized[39]. LI S S et al. reported the broadening of the bandwidth and suppression of the Time-Delay Signature (TDS) of chaos laser[40]. ZHANG Y N et al. numerically simulated the chaotic laser characteristics from a photoelectric feedback SL[41]. The nonlinear dynamics of 1 550 nm vertical-cavity surface-emitting SLs with negative optoelectronic feedback was analyzed[42]. However, the output power of chaotic laser based on SLs is relatively low. The average output power from DPSS passively Q-switched lasers could arrive from a few watts to several hundred watts, which provides the possibility of generating chaotic laser with high power. Hence, it may be a potential method for obtaining chaotic laser with high power based on DPSS lasers.

In this work, by adopting a laser diode emitting around 795 nm as a pump source, a Nd:LMA disordered crystal as a laser gain medium, a SESAM as a saturable absorber, we have experimentally demonstrated a Nd: LMA pulsed laser. Experimental results indicate that the diode-pumped Nd: LMA laser can operate at Q-switched state or PAC state depended on the pump power, where the chaos of PAC laser is judged through analyzing the autocorrelation curve, phase portrait, power spectrum and stochastic histogram of the Pulse-Peak Time Series (PPTS). For the Q-switched state and PAC state, the ranges of pump power are 4.8~8.6 W and 8.7~10.5 W, respectively. The maximum average output power of PAC laser arrives at about 814 mW under a pump power of 10.5 W.

1 Experimental setup

A uncoated optically polished a-cut Nd:LMA disordered crystal with dimensions of 3 mm×3 mm×5 mm and Nd^{3+} doping concentration of 5 at.% is used as a laser gain medium in the experimental system. The σ polarized emission and absorption spectra of the Nd: LMA disordered crystal have been measured, which includes two emission peaks at about 1 055 nm and 1 082 nm in the range of 1 000~1 100 nm and one absorption peak around 795 nm [21]. For matching with the absorption peak and improving the absorption efficiency of the Nd:LMA disordered crystal, a high-brightness fiber coupled laser diode with emitting laser peak at about 795 nm is employed as a pump source. The fiber has a core diameter of 105 μm and a numerical aperture of 0.22. The pump laser is focused into the Nd: LMA disordered crystal through a 1: 1 telescope system, resulting in a pump laser diameter in the Nd:LMA disordered crystal of about 105 μm. In order to reduce heat, the Nd:LMA disordered crystal is wrapped with indium foil and mounted on a water copper block. And the water is kept at a constant temperature of 18 ℃.

The experimental setups for the diode-pumped Nd:LMA laser operating at CW state and pulsed states, including Q-switched state and PAC state, are illustrated in Fig. 1. Under the CW state shown as Fig.1(a), a three-mirror-folded cavity is utilized, which is composed of a pump mirror 1(M1), a concave mirror 2(M2), and an output coupler (OC). M1 is a plane dichroic mirror, possessing high transmission at 796 ± 10 nm and high reflection at 1 000~1 100 nm. M2 has a Radius of Curvature (ROC) of 200 mm and a high reflection coating at 940~1 100 nm. OC is a plane mirror with the transmission of 15% at 1 000~1 100 nm. Under the pulsed states shown as Fig.1 (b), the laser cavity is composed of a pump mirror (M1), two concave mirrors (M2, M3), an output coupler (OC), and a SESAM. M3 has a high reflection coating at 900~1 100 nm and a ROC of 300 mm. The SESAM (BATOP GmbH) operates at 1 030~1 100 nm and has a modulation depth of 0.4%, an absorbance of 0.7%, a saturation fluence of 130 μJ/cm², and a relaxation time of 1 ps. In the experiment, the output characteristics of Nd:LMA laser are analyzed in the optical domain and time domain by employing an optical spectrum analyzer (Ando AQ6317C, 600~1 750 nm) and an oscilloscope (Agilent Technologies DS09254A), respectively. Laser powers are measured by using an optical power meter (Thorlabs-PM100D, Thorlabs-CAL).

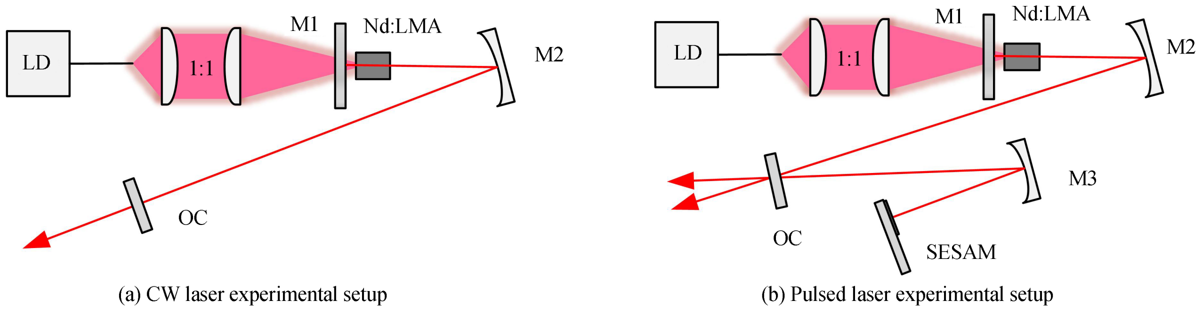
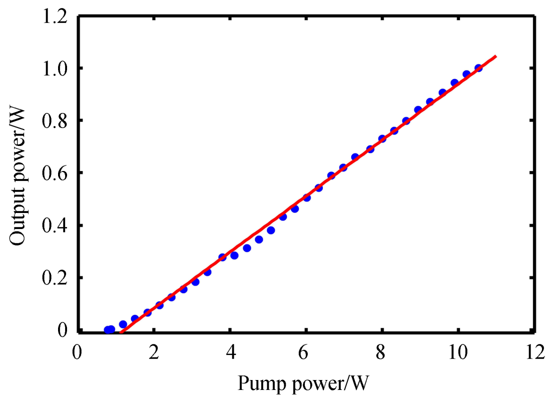


Fig.1 Schematic experimental setups

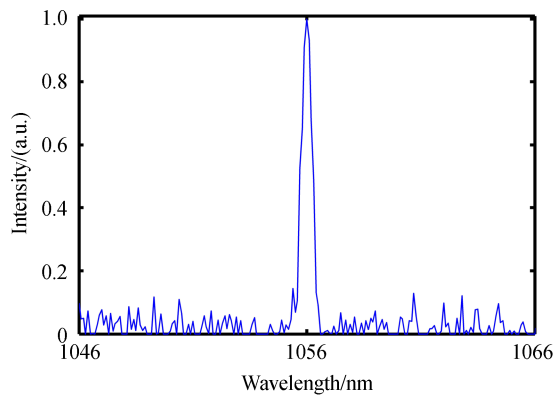
2 Experimental results and discussion

At first, the CW Nd:LMA laser performances are investigated by using the experimental setup without introducing SESAM (shown as Fig.1(a)). Fig.2(a) displays the dependences of the average output power on the pump power. Although the maximum output power of the laser diode can reach 12.0 W, in order to avoid damage the Nd: LMA disordered crystal, the pump power does not exceed 10.5 W during the experiment. From Fig.2(a), one can see that the pump threshold power is about 0.8 W and once the pump power exceeds

0.8 W, the average output power increases almost linearly with the increase of the pump power. When the pump power is increased to 10.5 W, the average output power arrives at about 1.0 W. And the corresponding slope efficiency and light-to-light efficiency are calculated to be about 10.7% and 9.5%, respectively. Fig.2(b) shows the measured optical spectrum for the CW Nd:LMA laser under a pump power of 6.0 W. The center wavelength of the CW Nd:LMA laser is about 1 056 nm.



(a) Dependence of the output power on the pump power



(b) The optical spectrum under a pump power of 6.0 W

Fig. 2 The output power and optical spectrum of the CW Nd:LMA laser

In order to make the Nd:LMA laser operates at pulsed states, a concave mirror (M3) and a SESAM are introduced to the laser cavity shown as Fig. 1 (b). With this experimental system, the Nd:LMA laser can operate at CW state, Q-switched state or PAC state, which is depended on the pump power. Fig.3 measures the average output power as a function of the pump power for the Nd:LMA laser operating at the three states and also shows the pump power ranges for the three states. Due to the M3 and SESAM introducing more intracavity loss, the pump threshold power increases up to about 1.8 W. As the pump power increases, the average output power increases in volatility. When the pump power is more than the pump threshold power, but relatively low (in the range of 1.8~4.7 W), the Nd:LMA laser operates at a CW state . And with the increase of the pump power (in the range of 4.8~8.6 W), the laser can enter a Q-switched state . When the pump power is in the range of 8.7~10.5 W, the Nd:LMA laser enters in a PAC state . The maximum average output power of the Nd:LMA laser operating at a Q-switched state and a PAC state are about 613 mW under a pump power of 8.6 W and 814 mW under a pump power of 10.5 W, respectively.

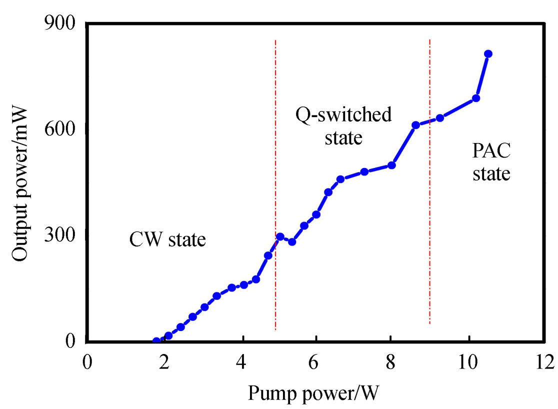


Fig. 3 The average output power as a function of the pump power of the Nd:LMA laser operating at CW state, Q-switched state, or PAC state

In order to analyze the performances of the Nd:LMA laser operating at a Q-switched state, the pulse time series, optical spectrum, and beam profile are measured and recorded under a pump power of 5.1 W. Fig.4(a) and 4(b) show the pulse time series with 0.001 s and 0.000 1 s time scales, respectively. From these two diagrams, one can see that the Nd:LMA Q-switched laser remains relatively stable and there are no multiple pulses, no harmonics, and no pulse splitting. Under this condition, the measured repetition frequency and pulse width are 117.7 kHz and 3.5 μs, respectively. Fig.4(c) shows the optical spectrum with a center wavelength at about 1 056 nm. The spatial distribution of the beam measured by a CCD camera shown as Fig.4(d), which indicates that the laser operates at a fundamental mode. Generally, for Q-switched lasers, the dependences of the repetition frequency and pulse width with the pump power is also an important parameter. Hence, we also record the repetition frequencies and pulse widths under different pump powers shown as Fig. 5. The pulse

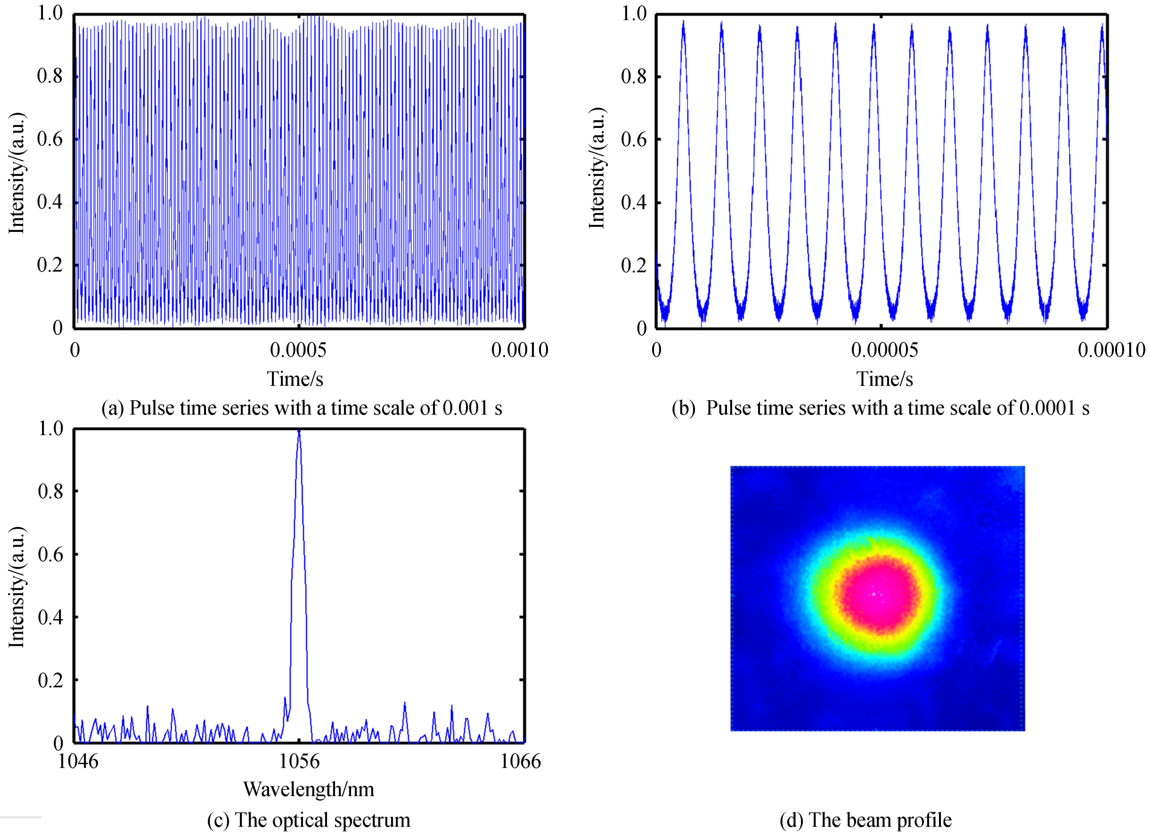


Fig.4 The performances of the Nd:LMA laser operating at a Q-switched state under a pump power of 5.1 W

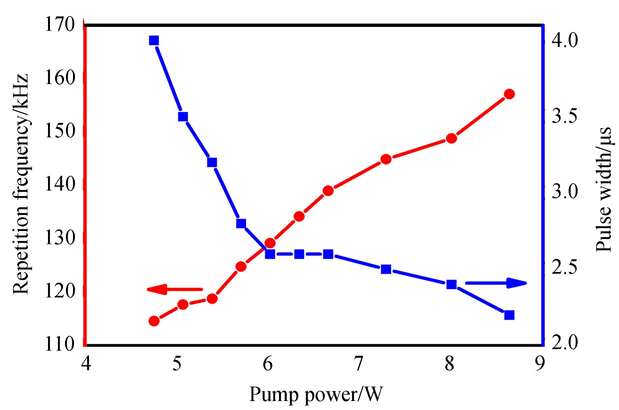


Fig.5 Dependence of pulse repetition rate and pulse width on pump power of the Nd:LMA laser operating at Q-switched state

widths gradually decrease while the repetition frequencies gradually increase with the increase of the pump power, which follows the laws of Q-switching. The variation ranges of the pulse widths and repetition frequencies are about 4.0~2.2 μs and 114.6~157.1 kHz, respectively.

When the pump power is in the range of 8.7~10.5 W, the pulse amplitudes of the Nd:LMA laser present as irregular and random distribution. In order to analyze this special performances of the Nd:LMA laser, the pulse time series and optical spectrum, and beam profile are measured and recorded under a pump power of 10.2 W. Fig.6(a), 6(b) and 6(c) represent the pulse time series with 0.05 s, 0.000 2 s, and 0.000 02 s time scales, respectively. From Fig. 6(a) and 6(b), it can be seen that the pulse amplitudes are irregular and random distribution. Fig. 6(c) shows a detailed view of the pulse, from which one can see that the pulse width and period are about 2.0 μs and 6.1 μs, respectively. Fig.6(d) shows the measured optical spectrum and the center wavelength is about 1 056 nm.

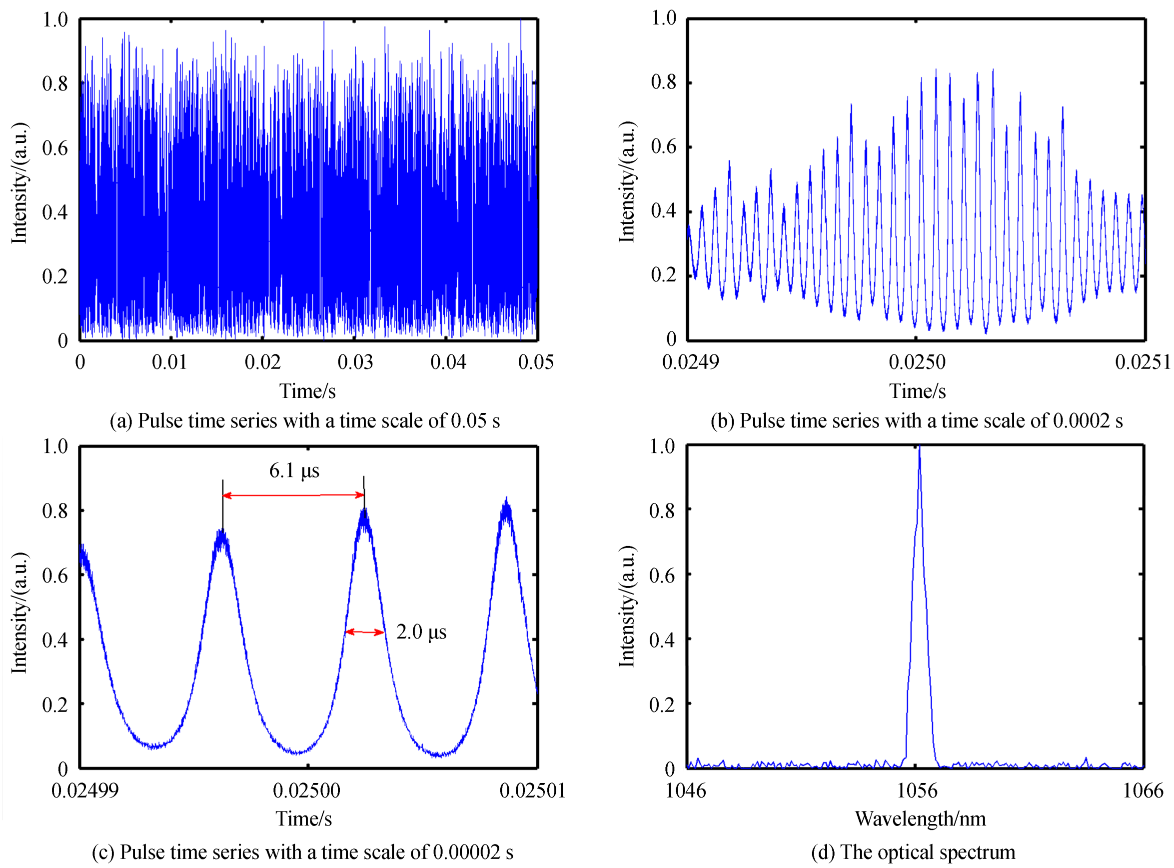


Fig.6 The performances of the Nd:LMA laser operating at a PAC state under a pump power of 10.2 W

In order to judge whether the pulse amplitudes of the Nd:LMA laser are chaotic, we extract the peak values of pulses and reconstructed a PPTS as shown the red dots and lines in Fig.7(a) and 7 (b). Fig.7(a) and 7 (b) represent the PPTS with 0.05 s and 0.000 2 s time scales, respectively. Further, for the reconstructed PPTS, the autocorrelation curve, phase portrait, power spectrum, and stochastic histogram are calculated and analyzed. Fig. 7 (c) shows the autocorrelation curve, and there is not apparent harmonic peak in the autocorrelation characteristics, which indicates the correlation of the PPTS is statistically insignificant. Fig.7(d) shows the corresponding phase portrait, which has no discernable structure and is a scattered distribution in a certain range. It reveals that there is no correlation between one pulse peak value at one round to the neighboring round and the trajectory in phase space move in a disordered form. The corresponding power spectrum is shown as Fig. 7(e), which is approximately continuous frequency range in the power spectrum. In addition, the stochastic histogram of the PPTS is shown as Fig.7(f), which distribution is relatively symmetrical. Hence, the pulse amplitudes of the Nd:LMA laser is judged as chaos through the autocorrelation curve, phase portrait, power spectrum, and stochastic histogram of the PPTS. It is worth noting that the chaos characteristics in this paper are similar to those of a DPSS Q-switched Nd:YAG laser reported by TANG D Y, which demonstrates that the DPSS passively Q-switched laser is a typical chaotic dynamic system, and its dynamics are determined by low dimensional chaotic attractors[24].

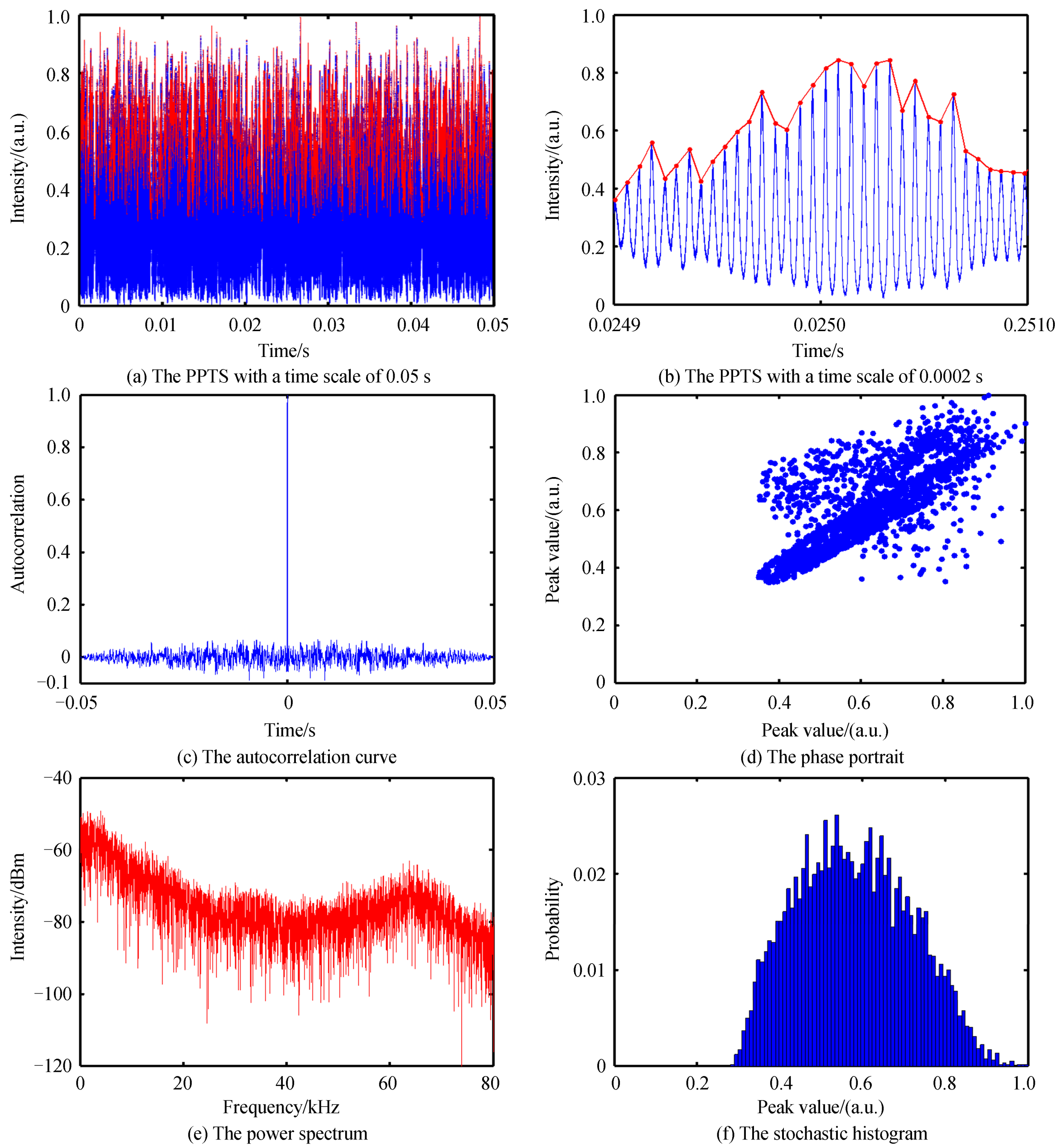


Fig. 7 The performances of PPTS of the Nd:LMA laser operating at a PAC state under a pump power of 10.2 W

3 Conclusion

In conclusion, by adopting a laser diode as a pump source, a Nd:LMA disordered crystal as a laser gain medium, a SESAM as a saturable absorber, a diode-pumped Nd: LMA pulsed laser are experimentally demonstrated. In the experimental system, the Nd:LMA pulsed laser can operate at Q-switched state or PAC state depended on the pump power, where the chaos of the PAC laser is proved through extracting by the autocorrelation curve, phase portrait, power spectrum, and stochastic histogram of the pulse-peak time series. When the pump power is in the range of 4.8～8.6 W, the Nd:LMA laser operates at a Q-switched state, and the repetition frequencies and pulse widths are in the range of 114.6～157.1 kHz and 4.0～2.2 μs, respectively. When the pump power is in the range of 8.7～10.5 W, the Nd:LMA laser operates at a PAC state. For a pump power of 10.5 W, the average output power of the PAC laser arrives at about 814 mW. However, the power of chaotic laser based on semiconductor lasers is only a few milliwatts. Therefore, this new experimental scheme for generating chaotic laser based on diode-pumped solid-state lasers may be a potential method for acquiring chaotic laser with high power.

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