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高重复频率铌酸锂电光调Q Nd：YVO_4激光器

商继芳[1,2,3]，孙军[1,2,3]，李清连[1,2,3]，吴婧[1,2,3]，张玲[1,2,3]，窦飞飞[4]，董潮涌[4]，许京军[2,3]
（1 南开大学 物理科学学院，天津 300071）
（2 南开大学 教育部弱光非线性光子学重点实验室，天津 300457）
（3 山西大学 极端光学协同创新中心，太原 030006）
（4 中国电子科技集团公司第二十七研究所，郑州 450000）

摘　要：研制了一种基于铌酸锂(LN)电光调Q的高重复频率窄脉宽短腔激光器.通过测量激光穿过置于正交偏振镜间的电光晶体后，透射强度随晶体上施加的脉冲高压的变化情况，探究了不同尺寸LN晶体中的压电振铃效应，并与磷酸钛氧铷(RTP)晶体中的压电振铃效应进行了比较.实验发现，块状LN晶体中的压电振铃效应严重，而小尺寸LN晶体中的压电振铃效应和RTP晶体中的相似，基本可以忽略.结合压电效应理论得出，压电振铃效应的强弱与外加电压大小及晶体固有的压电共振频率有关，电压越低，压电共振频率越大，压电振铃效应越弱.在此基础上，制备了可高重频应用的尺寸为1.2 mm×9 mm×9.4 mm的LN调Q开关，并实现了LN晶体的高重频调Q运转.激光增益介质采用具有较大受激发射截面和较短荧光寿命的Nd：YVO_4晶体，其一端镀有1.064 μm的全反膜，另一端沿布儒斯特角切割，从而省去了全反镜和偏振镜，缩短了腔长。泵浦源采用中心波长为808 nm的光纤耦合激光二极管.设计的激光器谐振腔长度仅为20 mm。在退压式电光调Q运转下，获得了最大重复频率为15 kHz、脉宽为5.4 ns、峰值功率为2.94 kW的稳定的激光输出.

关键词：固体激光器；脉冲激光；电光器件；铌酸锂；脉冲重复频率；电光Q开关；压电效应；窄脉冲宽度
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High-repetition-rate $LiNbO_3$ Electro-optic Q-switched Nd：YVO_4 Laser

SHANG Ji-fang[1,2,3], SUN Jun[1,2,3], LI Qing-lian[1,2,3], WU Jing[1,2,3],
ZHANG Ling[1,2,3], DOU Fei-fei[4], DONG Chao-yong[4], XU Jing-jun[2,3]
(1 *School of Physics*, *Nankai University*, *Tianjin* 300071, *China*)
(2 *MOE Key Laboratory of Weak-Light Nonlinear Photonics*, *Nankai University*, *Tianjin* 300457, *China*)
(3 *Collaborative Center of Extreme Optics*, *Shanxi University*, *Taiyuan* 030006, *China*)
(4 *The 27th Research Institute of China Electronics Technology Group Corporation*, *Zhengzhou* 450000, *China*)

Abstract: With a $LiNbO_3$ crystal as the electro-optic Q-switch, a compact Q-switched laser with a high repetition rate and a narrow pulse width was developed. The crystal was sandwiched between two crossed polarizers, then the variation of the laser transmitted intensity with the pulsed high voltage applied to the crystal was measured to investigate the piezoelectric ringing effects in $LiNbO_3$ crystals with different dimensions. Additionally, the piezoelectric ringing effects in $LiNbO_3$ crystals were compared with that of a $RbTiOPO_4$ crystal. The results show that the block $LiNbO_3$ crystal suffers enormously from

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First author: SHANG Ji-fang (1991—), female, Ph.D. degree candidate, mainly focuses on opto-electro functional materials and devices. Email: shangjifang@mail.nankai.edu.cn

Supervisor(Contact author): SUN Jun (1976—), male, professor, Ph.D. degree, mainly focuses on opto-electro functional materials and devices. Email: sunjun@nankai.edu.cn

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piezoelectric ringing, while the piezoelectric ringing in the miniaturized $LiNbO_3$ crystal is similar to that of the $RbTiOPO_4$ crystal and is negligible. Combining with the piezoelectric effect theory, it is derived that the acoustic ringing is influenced by the applied voltage and the piezoelectric resonance frequency, the acoustic ringing decreases with the decreasing of applied voltage and the increasing of piezoelectric resonance frequency. Based on these results, a miniaturized LN electro-optic Q-switch that can operate at a high repetition rate was prepared, its dimensions is 1.2 mm×9 mm×9.4 mm. The miniature LN crystal was successfully used for high repetition rate electro-optic Q-switching. A $Nd:YVO_4$ crystal possessing a large emission cross-section and a short fluorescence lifetime was used as the gain medium. One side of the $Nd:YVO_4$ crystal was high-reflection coated at 1 064 nm, and another side was cut along the Brewster angle, then a reflecting mirror and a polarizer was saved and the cavity length was shortened. The pump source was a fiber-coupled laser diode with a central wavelength of 808 nm. Based on the above design, a compact cavity with a length of only 20 mm was achieved. In the pulse-off Q-switching operation, a stable pulsed laser operating at a maximum repetition rate of 15 kHz with a pulse width of 5.4 ns and a peak power of 2.94 kW was obtained.

Key words: Solid state lasers; Pulsed lasers; Electro-optical devices; Lithium niobate; Pulse repetition rate; Electro-optic Q-switching; Piezoelectric effects; Short pulse width

OCIS Codes: 140.3538; 140.3540; 130.3730; 230.2090; 140.3480

0 Introduction

Lasers with a high repetition rate and a narrow pulse width have attracted considerable attention due to their extensive applications such as micromachining, laser ranging, remote sensing, medical treatment, etc[1-2]. A common way to realize such pulsed lasers is to Q-switch a diode-pumped solid state oscillator. The Q-switching can be classified into passive and active types. The passive Q-switching is beneficial to achieve narrow pulse width owing to the absence of additional polarizing optical elements. Unfortunately, its poor stability has limited its applications in many fields[3]. Active Q-switching enables a stable pulse energy and low temporal jitter at the repetition rate[4]. There are two main active Q-switch modes, the Acousto-Optic (AO) and the Electro-Optic (EO) Q-switching. The AO Q-switching is limited in many applications because of its tendency to produce a long pulse[5]. Compared with AO Q-switching, EO Q-switching has the advantages of better hold-off ability and faster switching rate[6], which enable the production of much shorter pulses.

Recently, several EO crystals such as β-BaB_2O_4 (BBO), $RbTiOPO_4$ (RTP), periodically poled $LiNbO_3$ (PPLN), $La_3Ga_5SiO_{14}$ (LGS) have been significantly investigated, and high repetition rate Q-switched lasers based on these EO crystals have been achieved. In 2010, BAI Y, et al. demonstrated a 532 nm green laser with a repetition rate of 10 kHz and a pulse width of 58.5 ns by using a BBO crystal as the EO Q-switch and a LBO crystal for frequency doubling[7]. In 2013, YU Y J, et al. reported a RTP EO Q-switched $Nd:GdVO_4$ laser with a repetition rate as high as 280 kHz and a pulse width of 18.4 ns[8]. In 2003, a novel EO Q-switch based on PPLN crystal was reported, the maximum repetition rate of the pulsed laser is 7 kHz with a pulse width of 12 ns and a peak power of 0.74 kW[9]. Recently, MA S H, et al. reported a LGS Q-switched laser operating at a repetition rate of 200 kHz with a pulse width of only 5.1 ns[10]. However, some intrinsic problems limit their further engineering applications, such the small EO coefficient of BBO, the low-symmetry structure and natural birefringence of RTP, the difficulty of achieving uniform periodic structure of PPLN and the optical activity of LGS[11].

$LiNbO_3$ (LN) crystal is one of the few EO crystals that have been practical, it has the advantages of large EO coefficient, broadband transmission spectral range, low insert loss, no water-solubility in air, etc. Additionally, LN crystals can operate stably in a wide temperature range[12]. Unfortunately, LN suffers enormously from piezoelectric ringing, and a conventional block LN Pockels Cell (PC) typically cannot be run at repetition rates exceed 1 kHz[13]. The piezoelectric ringing effects, though much influenced by the piezoelectric coefficient, is also influenced by the applied electro-field[10]. CHEN Y H, et al. had demonstrated a fast Q-switched laser with a repetition rate of 7 kHz by using a low-voltage PPLN crystal, and it was found that the low switching voltage together with the use of a high-gain laser medium has helped to reduce the transient elasto-optic ringing effect[9]. Thus, motivation is provided to design a low-voltage LN PC and investigate its Q-switching performance in high repetition rate lasers. For a LN PC in a transverse configuration, the quarter-wave voltage can be effectively reduced by enlarging the aspect ratio.

In this work, in consideration of the small intracavity beam size of most typical diode-pumped laser cavities, we prepare a miniaturized LN PC with a low Quarter-Wave Voltage (QWV). The piezoelectric ringing effect in the miniaturized LN PC is first investigated, and it is compared with those of a block LN PC and a RTP PC. The results indicate that the piezoelectric ringing effect in the miniaturized LN PC is negligible. Besides, the piezoelectric ringing effect is found to be influenced by the applied voltage and the piezoelectric resonance frequency of PCs. The high repetition rate Q-switching performance of the miniaturized LN PC is researched in a LD-pumped solid state oscillator with a Nd∶YVO_4 crystal as the gain medium. A stable pulsed laser operating at a repetition rate of 15 kHz with a pulse width of 5.4 ns and a peak power of 2.94 kW is obtained, which represents the highest repetition rate and minimum pulse width achieved so far in a LN Q-switched laser.

1 Experiments

1.1 Measurement of piezoelectric ringing

A low-voltage LN PC was firstly prepared. The LN crystal was cut along the Z-axis with dimensions of 1.2 mm×9 mm×9.4 mm ($X\times Y\times Z$). The transmission surface was polished precisely and Anti-Reflection (AR) coated at 1064 nm, the X surface was finely ground and plated with gold and chrome. Then the piezoelectric ringing effect in the miniaturized LN PC was investigated. A horizontal polarized laser at 1.06 μm was passed through the miniaturized LN PC sandwiched between two crossed polarizers. The LN was switched to its half-wave configuration using a homemade PC driver with a rise time of 7 ns. No approach was taken to damp any acoustic resonances. The transmitted signal was detected using an InGaAs photodetector connected to a 400 MHz digital oscilloscope. Besides, the drive voltage waveform was also recorded synchronously using a high voltage probe connected to the same digital oscilloscope. For the sake of contrast, the piezoelectric ringing effects in a block LN PC with dimensions of 7 mm×7 mm×28 mm ($X\times Y\times Z$) and a RTP PC with dimensions of 3 mm×3 mm×10 mm ($Y\times Z\times X$) were also measured. Both PCs were switched to their half-wave configuration with the same PC driver at the appropriate half-wave voltage. Additionally, a pulse-off EO driver with a fall time of 20 ns at various repetition rate was also used to switch the miniaturized LN PC.

1.2 Experiments of the Q-switched laser

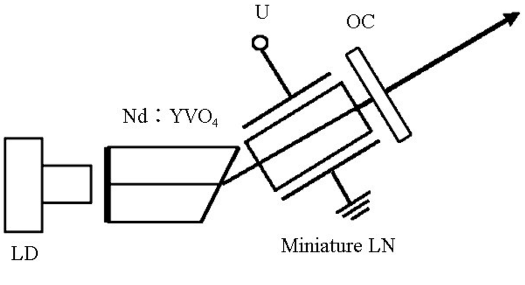


Fig.1 Schematic diagram of the miniature LN EO Q-switched Nd∶YVO_4 laser

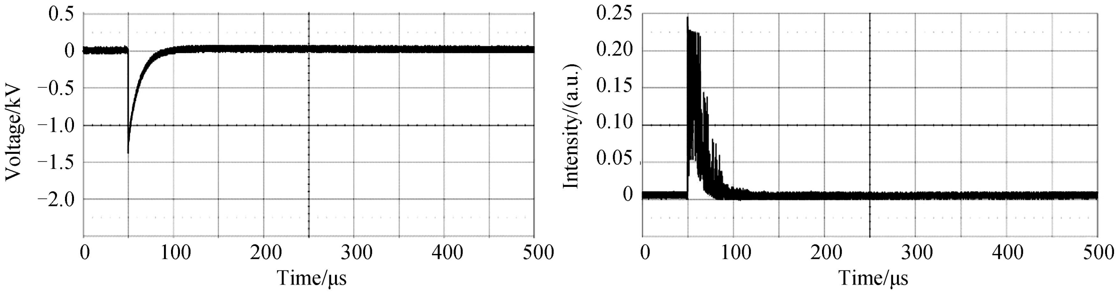
With the miniaturized LN PC, we constructed a high-repetition-rate LN Q-switched laser. The laser configuration is shown in Fig. 1. A Nd∶YVO_4 crystal possessing a large emission cross-section and a relatively short fluorescence lifetime was chosen as the gain medium, which is beneficial for obtaining high repetition rate laser output with narrow pulse width. The doping concentration was 1at%. One side of the Nd∶YVO_4 crystal was cut along a-axis, and the other side was Brewster-cut to produce a π-polarized laser. The sectional dimensions is 3 mm ×3 mm and the size of the longer edge along a-axis was 5 mm. The a-cut surface was polished and AR coated at 808 nm and High-Reflection (HR) coated at 1 064 nm. A fiber-coupled continuous wave laser diode with a center wavelength of 808 nm and a maximum output power of 1.41 W was used as pump source, which was incident on the a-cut surface directly. The fiber diameter is 50 μm with a numerical aperture of 0.22. The Output Coupler (OC) is a plane mirror with a transmission at 1 064 nm of 20%. The a-cut surface of the Nd∶YVO_4 crystal and the OC formed the resonant cavity with a length of about 20 mm. The miniature LN Q-switch operated in the pulse-off Q-switching mode, the voltage was supplied with the pulse-off EO driver. The single pulse energy was measured by an energy meter and the average output power was measured by a power meter. The Q-switched laser pulses were detected by an

InGaAs fast photodiode connected to a 400 MHz digital oscilloscope.

2 Results and discussion

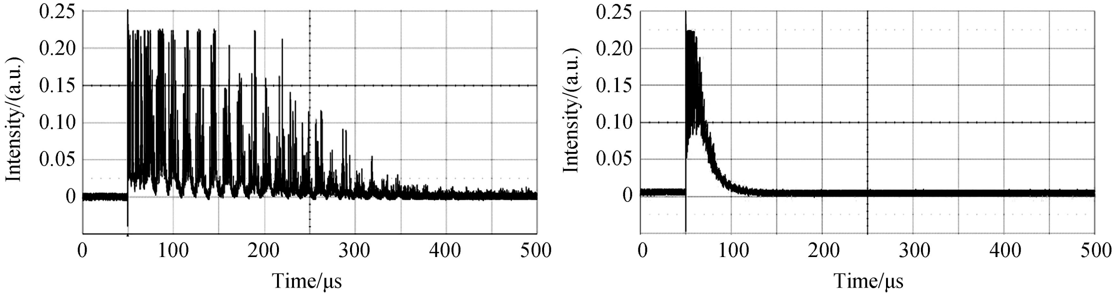
2.1 Piezoelectric ringing

A dramatic demonstration of the low piezoelectric ringing in the miniaturized LN PC is shown in Fig.2, where the miniaturized LN PC is directly compared to the block LN PC and the RTP PC. Both PCs were switched with the homemade PC driver. The intensity transmitted through the conventional block LN PC varies greatly and it does not follow the decay of the applied high voltage pulse. Whereas the pulse switched by the miniaturized LN PC cleanly follows the applied high voltage pulse, which is similar to that of the RTP PC. The difference is thought to be due to the different intensity of piezoelectric ringing in the crystals. For a crystal with large piezoelectric effects, when it subjected to high voltage pulses, piezoelectric effects can give rise to acoustic waves in the crystal, the acoustic waves continue to modulate the crystal birefringence through the elasto-optic effect long after the high voltage pulse is applied. As a result, there was still high intensity transmitted signals long after the voltage dropped to zero. Undoubtedly, the piezoelectric ringing effects will impair the performance of the PC. From Fig.2, it can be derived that the block LN PC suffers enormously from piezoelectric ringing, while the piezoelectric ringing in the miniaturized LN PC is similar to that of the RTP PC and is very weak. RTP crystals are well known to be free from acoustic ringing[14], thus it is deduced that the piezoelectric ringing in the miniaturized LN PC is negligible.



(a) Applied voltage pulse

(b) Temporal behavior of the intensity transmitted through the RTP PC



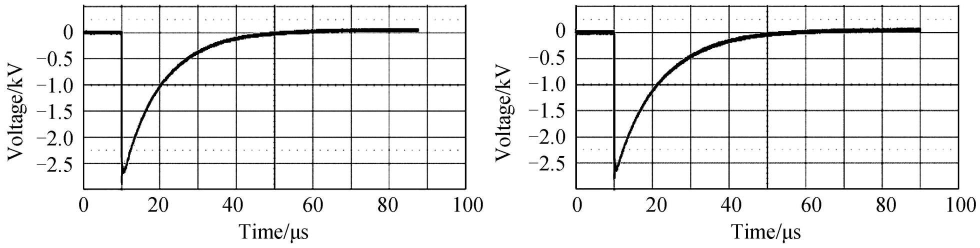
(c) Temporal behavior of the intensity transmitted through the block LN PC

(d) Temporal behavior of the intensity transmitted through the miniature LN PC

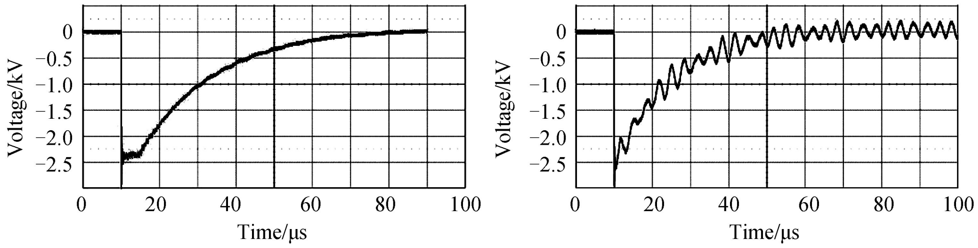
Fig.2 Qualitative comparison of piezoelectric ringing in miniature LN, block LN and RTP

In addition, it is found that an oscillation occurs on the trailing edge of the voltage pulse once it was applied to a PC. The oscillation amplitude varies with PCs, as shown in Fig.3. Under the same voltage, the oscillation amplitude of the voltage pulse applied to the block LN PC is much higher than that applied to the miniature LN PC. The voltage waveform applied to the RTP PC is smooth with no evident oscillation. The oscillation frequencies for the block LN PC and the miniature LN PC were measured to be 0.3 MHz and 1.64 MHz. By using the expression and parameters given in literature[15], the theoretical piezoelectric resonance frequency for the two PCs were calculated to be 0.27 MHz and 1.56 MHz, which demonstrates that the oscillation was caused by piezoelectric effects. Besides, it implied that the oscillation amplitude can be another indicator of piezoelectric ringing intensity. To investigate the dependence of the piezoelectric ringing on the dimensions of LN crystal, another two LN crystals with the dimensions of 3.8 mm×9 mm

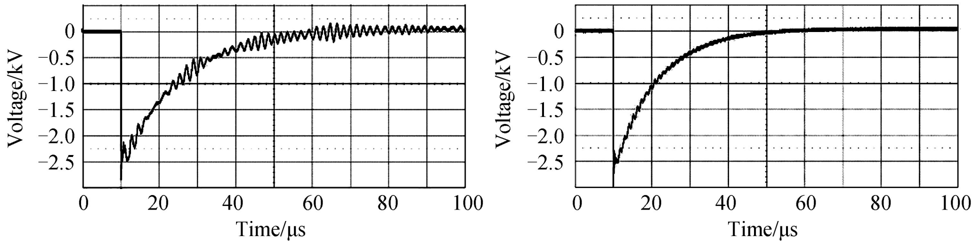
×19 mm and 2.3 mm×2.6 mm×9.4 mm were employed, they are labeled as LN_1 and LN_2. The voltage waveforms applied to these two LN crystals are shown in Fig.3(e) and Fig.3(f). Clearly, the oscillation amplitude of voltage pulses for these two crystals are higher than that for the miniature LN and lower than that for the block LN, and the voltage oscillation amplitude for LN_1 is higher than that for LN_2. The oscillation frequencies for LN_1 and LN_2 were measured to be 0.55 MHz and 0.9 MHz, which are consistent with the theoretical piezoelectric resonance frequency of 0.5 MHz and 0.83 MHz. Based on the above results, it is derived that the piezoelectric ringing decreases with the increasing of piezoelectric resonance frequency. The amplitude of the high frequency component of the voltage pulse decreases with the increasing of frequency[15]. Thus as the piezoelectric resonance frequency increases, the amplitude of the voltage component that involves in piezoelectric resonance decreases, as a result, the piezoelectric ringing is weaker. Since the piezoelectric resonance frequency is determined by the dimensions of crystals, the piezoelectric ringing varied with the dimensions of LN crystals. The piezoelectric ringing in the miniature LN PC is weaker due to its larger piezoelectric resonance frequency.



(a) No-load (b) RTP



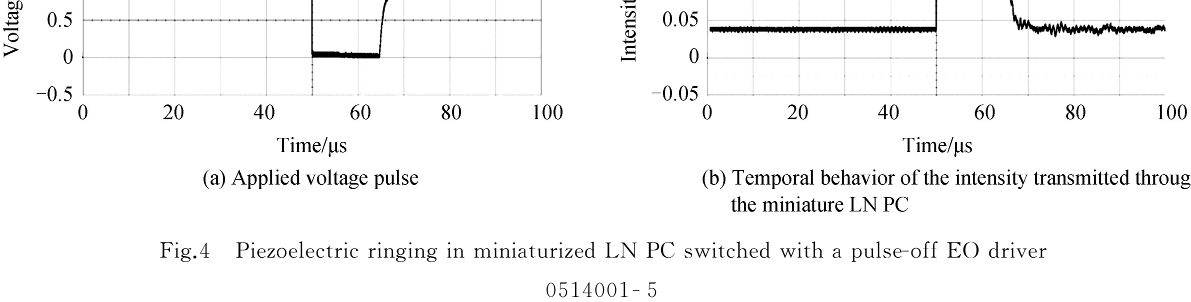
(c) Miniature LN (d) Block LN



(e) LN_1 (f) LN_2

Fig.3 Waveform of voltages applied to different PCs

The piezoelectric ringing in the miniaturized LN PC which was switched with the pulse-off EO driver is also negligible, as shown in Fig.4. Besides, there was no discernable change in performances when the repetition rate varied from 1 Hz to 15 kHz.

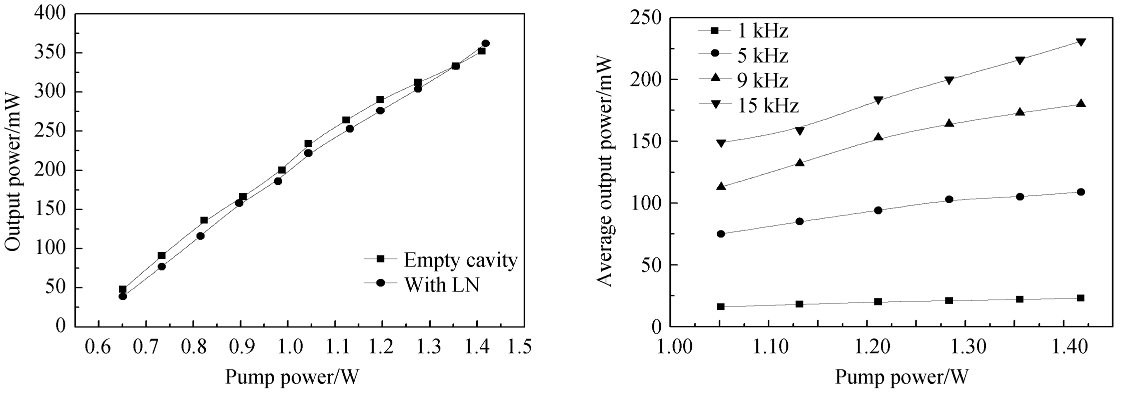


(a) Applied voltage pulse (b) Temporal behavior of the intensity transmitted through the miniature LN PC

Fig.4 Piezoelectric ringing in miniaturized LN PC switched with a pulse-off EO driver

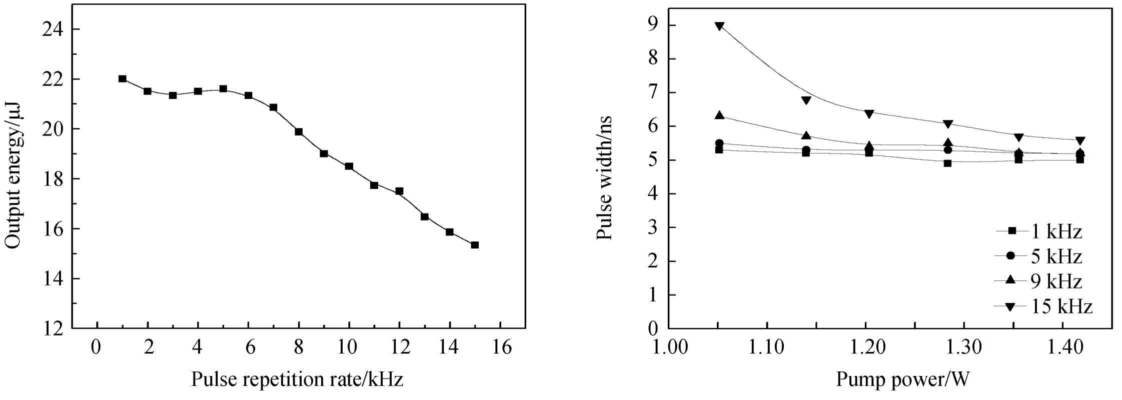
2.2 Q-switched laser

The high-repetition-rate Q-switching performance of the miniaturized LN PC was experimentally researched. At first, we studied the output performance of the Continuous Wave (CW) laser without any inserting elements. With an OC transmission of 20%, the optimized output power was achieved. Fig.5(a) shows the output power as a function of the absorbed pumped power. At a pump power of 1.41 W, the maximum output power of 352 mW was obtained with a conversion efficiency of 25% and a threshold power of 0.6 W. When the miniaturized LN PC was inserted into the cavity, the threshold power increased and the output decreased slightly. By applying a high voltage pulse to the LN PC, a Q-switched laser is obtained. It should be noted that the applied voltage is only 280 V, which is much less than the quarter-wave voltage. This is because the hold-off state can be achieved as long as the cavity loss is slightly greater than the gain, so the full 90°round trip polarization rotation is usually unnecessary at low gain levels[9], which means that the full quarter-wave voltage may not always be required in the pulse-off regime. The dependence of the average output power on the pump power at various repetition rate is shown in Fig.5(b). The output power increases both with the increase of the pump power and repetition rate. At a repetition rate of 15 kHz, the maximum output power was measured to be 230 mW with a pump power of 1.41 W, corresponding to a dynamic-static ratio of 65.3%. The output energy was stable with a variation of 6.3%. A plot of the output energy versus the repetition rate at a pump power of 1.41 W is presented in Fig.5(c). The energy is almost invariable under 5 kHz, but decreased rapidly with the increase of the repetition rate above 5 kHz. A similar changing tendency can be found in literature[16]. The results are consistent with the theoretical analysis[17].



(a) Output power versus pump power of CW laser

(b) Output power versus pump power of Q-switched pulsed laser

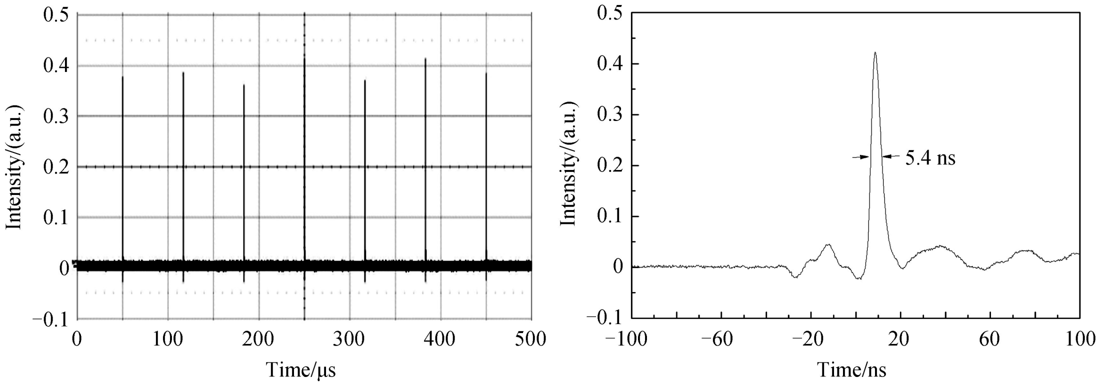


(c) Output energy versus pulse repetition rate

(d) Pulse width vs. pump power at different repetition rates

Fig.5 The performances of CW and Q-switched pulsed lasers

The pulse behavior of the Q-switched laser was measured by a photodiode connected to an oscilloscope. No multiple-pulse is formed at various pump powers and repetition rates. The pulse train obtained at a repetition rate of 15 kHz is shown in Fig.6(a). It is clear that both the pulse strength and pulse interval are stable, the instability of pulse strength is approximately 6.8%. It demonstrates that the Q-switching performance was not influenced by the piezoelectric ringing effect. The pulse widths at various repetition rates are plotted versus the pump power in Fig.5(d). The dependence of the pulse width on the pump power is not obvious, which may be explained by the following reasons. On the one hand, the decrease in the number of round trips may not be significant due to the small increase in the pump power. On the other hand, the round-trip time is small due to the short cavity length, even if the number of round trips is decreased slightly, the variation in the pulse width is not obvious. The shortest pulse width at the repetition rate of 15 kHz is 5.4 ns with a pump power of 1.41 W, the pulse profile is shown in Fig.6(b). The maximum peak power is calculated to be 2.94 kW for a repetition rate of 15 kHz.



(a) Pulse train with a repetition rate of 15 kHz

(b) Pulse profile with a pulse width of 5.4 ns

Fig.6 Pulse behavior of the Q-switched laser

The typical beam profile of the Q-switched laser at a repetition rate of 15 kHz with a pump power of 1.41 W was measured with a laser beam analyzer (M2-200, Spiricon, Inc.). The distributions of the laser intensity and the measured beam diameter at different distance from a lens (f=250 mm) are shown in Fig.7. Note that the images captured by the CCD were rotated by 90° relative to the original beam. By fitting Gaussian beam standard expression to these data, the beam-quality factors were estimated to be $M_x^2=3.31$ and $M_y^2=4.67$. The waist radiuses of the Q-switched laser were estimated to be $\omega_x=0.362$ mm and $\omega_y=0.406$ mm. The non-circular symmetry of the laser beam is thought to be caused by that one side of the Nd : YVO_4 crystal was Brewster-cut. Additionally, by employing a rotating quarter-wave plate method[18], the polarization degree of the laser was estimated to be 0.972 1. At these conditions, there was no damage observed in any component of the laser cavity. Thus, the miniature LN PC can be expected to operate in lasers with higher peak power and higher repetition rate.

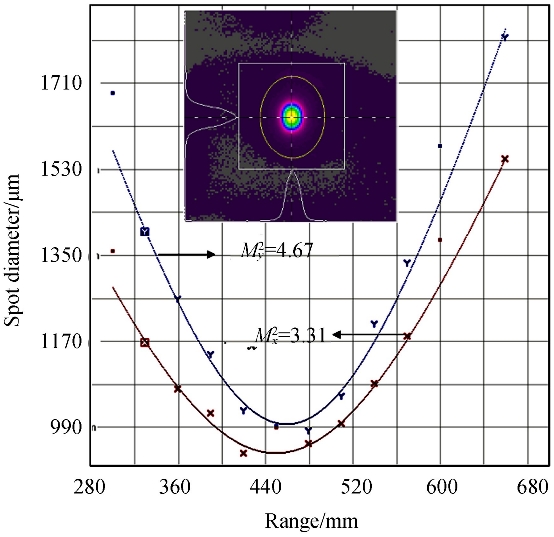


Fig.7 Beam quality for 15 kHz Q-switched laser at a pump power of 1.41 W

3 Conclusion

We have investigated the piezoelectric ringing effects in LN PCs with different dimensions and in a RTP PC. The results demonstrate that the piezoelectric ringing effects in LN PCs is influenced by the applied voltage and the piezoelectric resonance frequency of PCs. The piezoelectric ringing effect in the miniature LN PC are negligible owing to its lower switching voltage and larger piezoelectric resonance frequency. With the miniature LN crystal as the EO Q-switch, we have successfully demonstrated a high repetition rate Q-switched Nd : YVO_4 laser. At a pump power of 1.41 W, a stable pulsed laser operating at a repetition rate of 15 kHz with a pulse width of 5.4 ns and a peak power of 2.94 kW was obtained. This work represents the highest repetition rate and minimum pulse width achieved so far in a LN Q-switched laser.

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