

Article

Burst-Mode 355 nm UV Laser Based on a QCW LD-Side-Pumped Electro-Optical Q-Switched Nd: YAG Laser

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Abstract: In this paper, a high-repetition-rate, high-peak-power burst-mode nanosecond 355 nm UV laser was demonstrated. A quasi-continuous wave (QCW) laser diode (LD) side-pumped electro-optical (EO) Q-switched burst-mode Nd: YAG laser was performed as the fundamental laser source. Under the pumping duration of 250 μ s and a burst repetition rate of 100 Hz, the pulse energy of 20 kHz burst-mode UV laser reached 5.3 mJ with a single pulse energy of 1.325 mJ, pulse width of 68 ns, resulting in a peak power of 19.49 kW. The as-generated millijoule burst-mode UV laser has great potential for high-end processing of laser lift-off, annealing and slicing in display semiconductor fields.

Keywords: burst-mode; 355 nm UV laser; QCW LD-side-pumped

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1. Introduction

With the advantages of large photon energy and high material absorption efficiency, the high energy nanosecond 355 nm UV laser plays significant roles in the high-end manufacturing of the display semiconductor field (mobile phone, tablets, notebooks, automotive, aerospace, and wearable electronics), including micro-LED laser lift-off [1–3], wafer dicing [4,5], thin film ablation [6–8], cover glass cutting [9,10], PCB drilling [11,12], etc. Excimer lasers with high energy output have been widely used for the above applications. The high-cost maintenance, low beam quality, and large size limits its further applications. With the development of diode-pumped solid-state lasers (DPSSLs) and the innovation of the large sized and high quality nonlinear crystals, the solid-state UV lasers based on the nonlinear frequency conversation technique exhibits the great potential to replace excimer lasers with the merits of high beam quality, compactness, and low-cost maintenance [13,14]. What's more is that it can operate in burst mode, which can greatly improve machining accuracy, quality, and efficiency [15–17].

Burst mode lasers can generate high pulse energy with high pulse repetition rate and low average power by grouping a series of sub-pulses into short bursts, motivated by the requirements of certain laser applications, including laser material processing [18], optical metrology [19], lidar [20] and laser detection [21], the research of chemical species and thermodynamic quantities [22,23]. Burst mode lasers can be generated by mode-locked lasers with pulse pickers and amplifiers [24], mode-locked lasers with pulse splitter [25], Q-switched mode locking lasers [26,27], and Q-switched laser techniques [28]. Compared with other methods, Q-switching is the most effective for generating millijoule nanosecond and sub-nanosecond burst pulses with repetition rates in the scale of kHz–100 kHz. Typically, Q-switched burst mode lasers can be pumped by either continuous-wave (CW) or quasi-continuous-wave (QCW) laser diodes (LD). QCW-LD pumping allows the laser

crystal to cool down sufficiently to achieve a much higher pulse energy and better beam quality than that of regular CW pumping [29,30]. Recently, Wentao Wu et al. reported a cavity-dumped burst-mode Nd: YAG MOPA laser with burst energy, peak power and pulse duration of 1.89 J, 2.87 MHz, ~3 ns, respectively, with the repetition rate of 100 kHz in 10 Hz pulse train [31]. Xudong Li et al. demonstrated a burst-mode acousto-optically Q-switched YVO₄/Nd: YVO₄ Q-switched laser, generating 10–500 sub-pulse per burst at a 1 Hz burst repetition rate, the corresponding single pulse energy of ~90 µJ and pulse width of 38.7 ns were obtained at the pulse repetition rate of 500 kHz [32]. However, the burst repetition rate was limited to 1 Hz and 10 Hz, which is inadequate for a laser source designed for the efficient processing of materials. The low repetition rate does not meet the requirements of high-efficiency material processing, thereby constraining advancements in processing efficiency.

In this paper, a 355 nm burst-mode UV laser based on frequency, the triple QCW-LD side-pumped electro-optical (EO) Q-switched Nd: YAG module, was demonstrated. Over 30 mJ of pulse energy of 1064 nm fundamental burst-mode laser was generated under the pump duration of 250 µs, the burst repetition rate of 100–200 Hz, and the sub-burst repetition rates of 20–50 kHz. Subsequently, 355 nm burst-mode laser was generated with a burst energy of 5.3 mJ, comprising single pulses each with an energy of 1.325 mJ within the burst. The pulse width was 68 ns, resulting in a peak power of 19.49 kW. The laser operates in a low-duty-cycle, quasi-continuous-wave (QCW) pumped configuration, effectively mitigating thermal lensing effects. This configuration represents an innovative design approach. This approach not only allows for flexible adjustment of the burst repetition rate and pulse number, but also ensures consistent pulse output. The burst-mode 355 nm UV laser would have great potential for micro-LED laser lift-off and electronic device laser annealing.

2. Experimental Section

Figure 1 shows the schematic of the experimental setup of the 355 nm UV burst-mode laser, including an oscillator, a second harmonic generation (SHG) and third harmonic generation (THG) units. The burst-mode 1064 nm oscillator consists of a QCW-LD side-pump Nd: YAG module, a quarter wave plate (QWP), an electro-optic modulator (EOM), a thin film polarizer (TFP), and two end mirrors (M1 and M2 in Figure 1). The length of the oscillator cavity is 60 cm. The peak pump power of the 808 nm QCW-LD is 1200 W with pulse duration and pulse repetition rate set to 250 µs and 100–200 Hz. A Nd: YAG crystal rod with Nd³⁺-doping concentration of 0.6 at.% and the dimension of Φ3 × 75 mm³ is used as the gain medium, and the two ends are anti-reflection (AR) coated at 1064 nm. The cooling water temperature is set to 20 °C. M1 is a flat mirror with high transmittance (HT) coated at 808 nm and high reflectance (HR) coated at 1064 nm, while M2 is a flat with partial transmittance coated at 1064 nm. TFP is selected with an incident angle of 56°. BBO electro-optical modulator with a quarter-wave voltage setting of about 2900 V is chosen for high-repetition-rate sub-burst pulse generation.

A convex lens L1 and a concave lens L2 are used as a beam reducer (BR). The 1064 nm burst-mode laser is collimated by BR before entering into the SHG and THG harmonic generation unit. A type I phase-matched LBO crystal ($\theta = 90^\circ$, $\phi = 10.8^\circ$) with a size of 5 × 5 × 25 mm³ is used for SHG generation. The two end faces of the SHG LBO crystal are AR-coated at 1064 nm and 532 nm. A type II phase-matched LBO crystal ($\theta = 42.4^\circ$, $\phi = 90^\circ$) with a size of 5 × 5 × 20 mm³ is used for THG generation. The front surface of the THG LBO is AR coated at 1064 nm and 532 nm, while the rear surface is AR-coated at 355 nm and HT coated at 1064 nm and 532 nm. The crystals are placed in a water-cooled heat sink, with the water-cooling temperatures set to 40 °C for SHG and 25 °C for THG. The output 355 nm UV laser is separated using two dichroic mirrors (M3 and M4). The laser output power was recorded with a power meter (PM100D, Thorlabs, Newton, NJ, USA). The pulse repetition rate and pulse duration were recorded using a digital oscilloscope (Tektronix, DPO7104, Beaverton, USA) and detector (New Focus, bandwidth of 1 GHz).

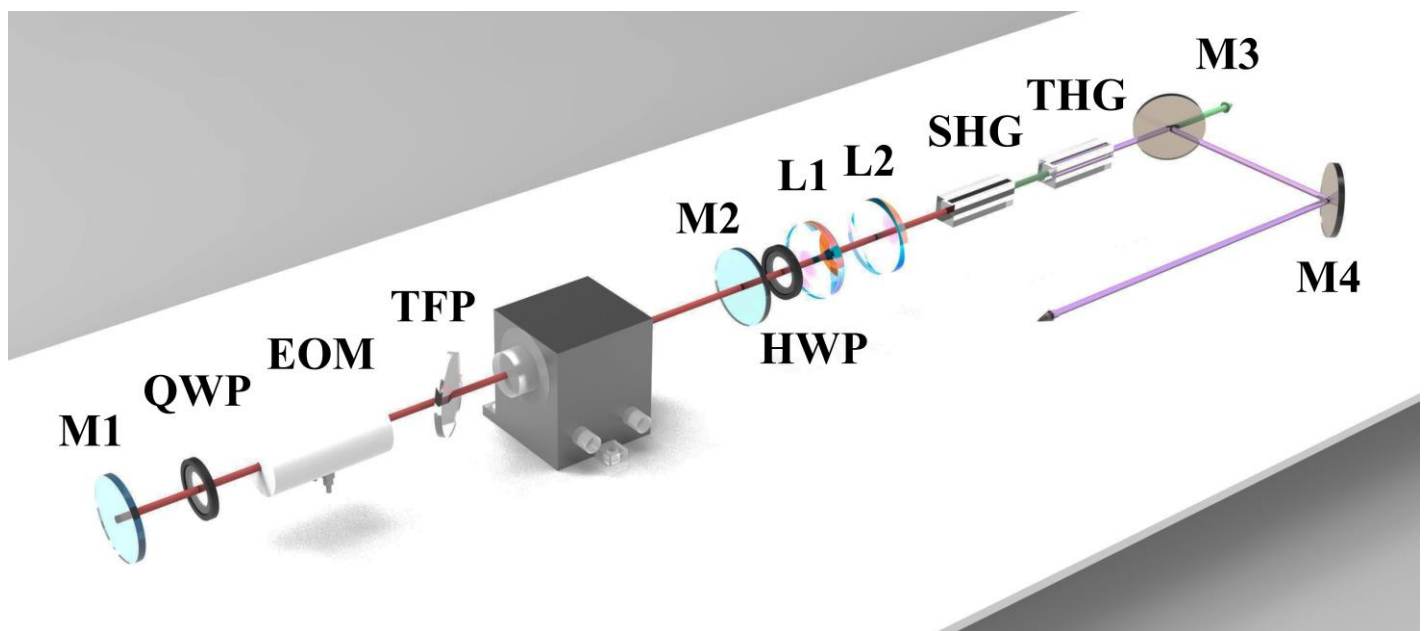


Figure 1. Schematic diagram of experimental setup for the 355 nm UV burst-mode laser. QWP, quarter-wave plate; EOM, electro-optical modulator; TFP, thin film polarizer; HWP, half-wave plate; SHG, second harmonic generation; THG, third harmonic generation.

3. Results and Discussions

Figure 2a illustrates the relationship between the 1064 nm burst-mode output energy and the peak pump power for output coupler (OC) transmittances of 10%, 30% and 50%, respectively. The pump repetition rate, pulse duration, and Q-switched repetition rate were set to 100 Hz, 250 μ s, and 20 kHz, respectively. When using an OC transmittance of 50%, a maximum burst output energy of 30.3 mJ was achieved at a peak pump power of 780 W. With an OC transmittance of 30%, the maximum burst output energy increased slightly to 30.4 mJ, whereas at 10% OC transmittance, the maximum output energy reached 26.4 mJ. Figure 2b shows the single pulse duration of the output laser at different transmittances. Since the pulse duration of the 1064 nm laser can be shortened by increasing the transmittance of the output mirror, the laser pulse width generated by the OCs of 10% and 30% transmittance decreased accordingly, measuring 88.6 ns and 77.5 ns, respectively. However, excessively high transmittance can lead to pulse tailing, resulting in a wider pulse width. Consequently, the pulse width generated by the OC of 50% transmittance was relatively wider, around 94.9 ns. Therefore, considering both output energy and pulse width, we selected an OC transmittance of 30% for the following experiment.

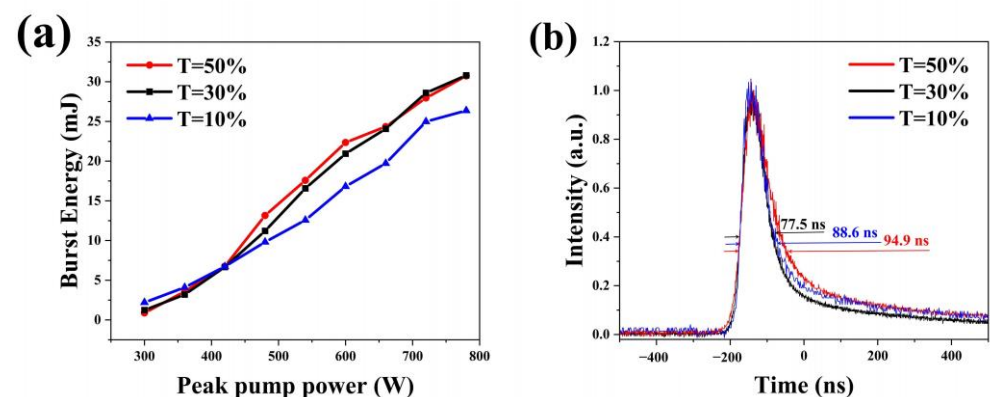


Figure 2. (a) The 1064 nm burst laser energy versus the peak pump power for various output transmittances; (b) The single pulse profile at different output transmittances under the peak pump power of 780 W.

Figure 3 shows the burst mode laser output performances with the pump repetition rates of 100 Hz and 200 Hz and the sub-pulse repetition rates at 20 kHz, 40 kHz, and 50 kHz. As shown in Figure 3g, as the peak pump power increased, the output energy reached 30.4 mJ at the peak pump power of 780 W. It can be observed that the maximum output energy at different Q-switched repetition rates remains relatively consistent, with all values around 30 mJ. The pump repetition rate had some impact on the burst energy, likely due to the varying thermal effects generated by the laser at different pump repetition rates. At 200 Hz, the thermal effect was more pronounced compared to 100 Hz, causing the average output energy to slightly decrease from 30.4 mJ to 30.2 mJ. However, the overall difference remained minimal. Figure 3a–f show the pulse profiles and pulse trains at different Q-switched repetition rates for pump repetition rates of 100 Hz and 200 Hz, with the highest output burst energy of 30 mJ. The output laser pulse width increased with increasing Q-switched repetition rate. Under the repetition rates of 20, 40, and 50 kHz, the number of sub-pulses obtained in each burst was 4, 9, and 11, and the pulse sequences were relatively neat, which proved that the power stability of the sub-pulses within the burst was excellent. The beam quality at the highest output energy of the 1064 nm laser at different pump repetition rates was assessed with the beam quality factors for two directions were measured to be $M_x^2 = 2.49$, $M_y^2 = 2.48$ for 100 Hz, and $M_x^2 = 3.81$, $M_y^2 = 3.90$ for 200 Hz, respectively, as shown in Figure 3h. Due to thermal effects, the beam quality at 200 Hz repetition rates was slightly worse. The two-dimensional spatial intensity distribution of the laser beam was inserted in Figure 3h, suggesting that the 1064 nm laser consistently maintained a Gaussian mode under burst-mode output. Figure 3i presents the output spectrum obtained under 30 mJ of 1064 nm fundamental laser, with a central wavelength of 1064.4 nm.

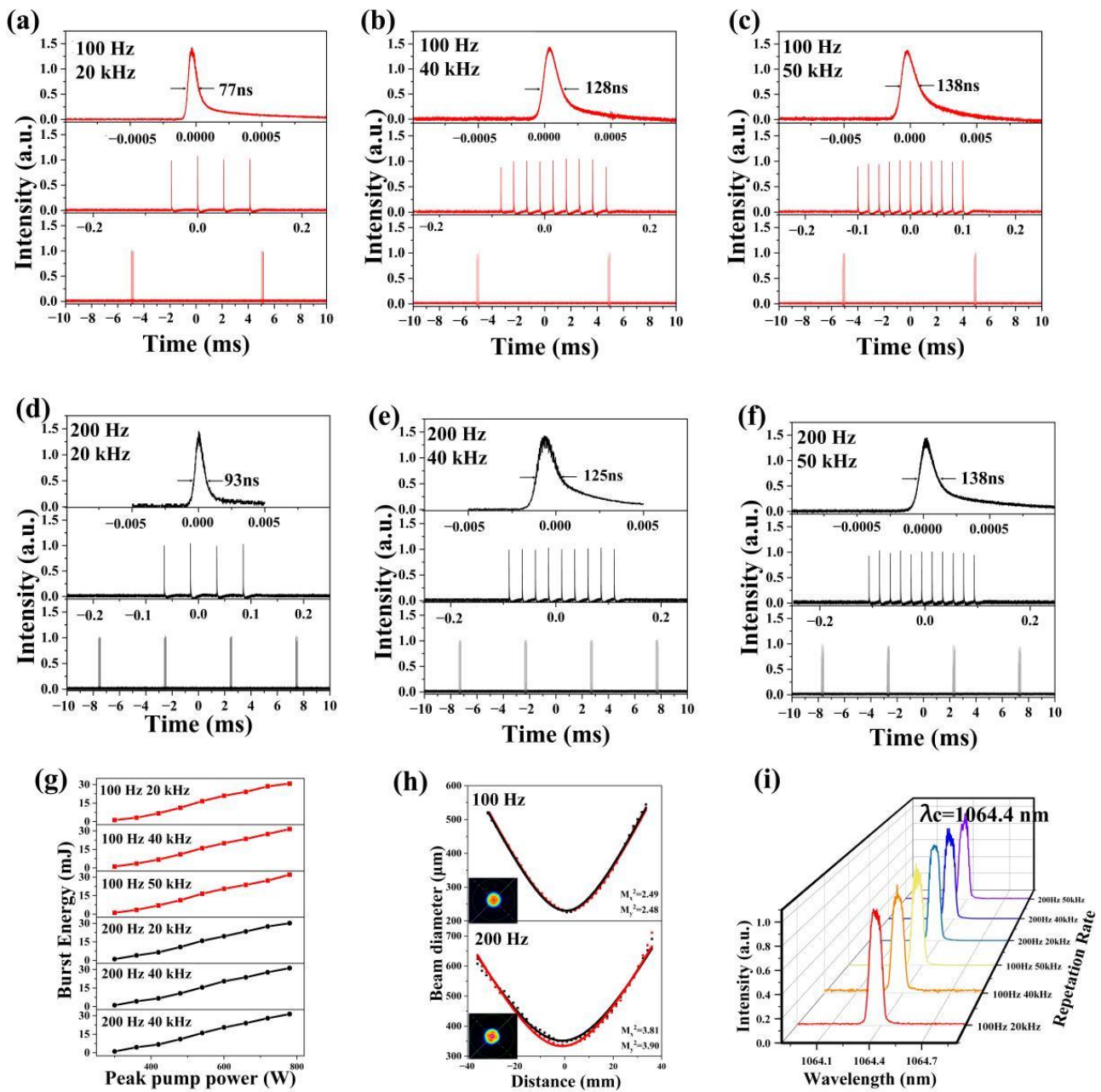


Figure 3. The single pulse and pulse sequence shapes for 20k, 40k, 50k Hz sub-pulse repetition rates at burst repetition rate 100 Hz (a–c), 200 Hz (d–f); (g) the output 1064 nm burst laser energy versus peak pump power at different repetition rates; (h) beam quality and spatial intensity distribution for 100 Hz and 200 Hz at output energy of 30 mJ; (i) the spectrogram of the 1064 nm output laser.

To protect the LBO crystals and coatings from damage, the incident single-pulse energy was carefully maintained at a density of 4 J/cm². Figure 4g,h illustrate the relationship between SHG efficiency at 532 nm and the burst energy of the incident 1064 nm laser at various pump repetition rates, respectively. The output energy of the 532 nm laser remained consistently around 12 mJ at the same pump repetition rate, due to the constant energy density of the 1064 nm single pulse incident into the LBO crystal. However, varying beam quality of the 1064 nm laser at 100 Hz and 200 Hz pump repetition rates led to a slightly lower 532 nm laser output at 200 Hz compared to that of 100 Hz. At a pump repetition rate of 100 Hz, the 532 nm laser energy at sub-burst repetition rates of 20 kHz, 40 kHz, and 50 kHz were 12.3 mJ, 13.3 mJ, and 12.4 mJ, respectively. While at 200 Hz, the

energies were 11.5 mJ, 12 mJ, and 9 mJ. Among these, the highest output energy was observed at 40 kHz, with 13.3 mJ and 12 mJ for the 100 Hz and 200 Hz pump repetition rates, respectively, corresponding to the SHG conversion efficiencies of 44.3% and 40.2%. As shown in Figure 4a–f, the pulse widths were reduced after frequency doubling, decreasing from 77, 128, and 138 ns to 71, 116, and 119 ns at 100 Hz, and from 93, 125, and 138 ns to 83, 118, and 125 ns at 200 Hz pump repetition rate, respectively. Additionally, the pulse trains remained consistent after repetition rate doubling, indicating that the power stability of the 532 nm laser sub-pulse was effectively maintained. Figure 4i presents the spectrogram of the 532 nm output laser, measured at the highest output energy with a central wavelength of 532.5 nm.

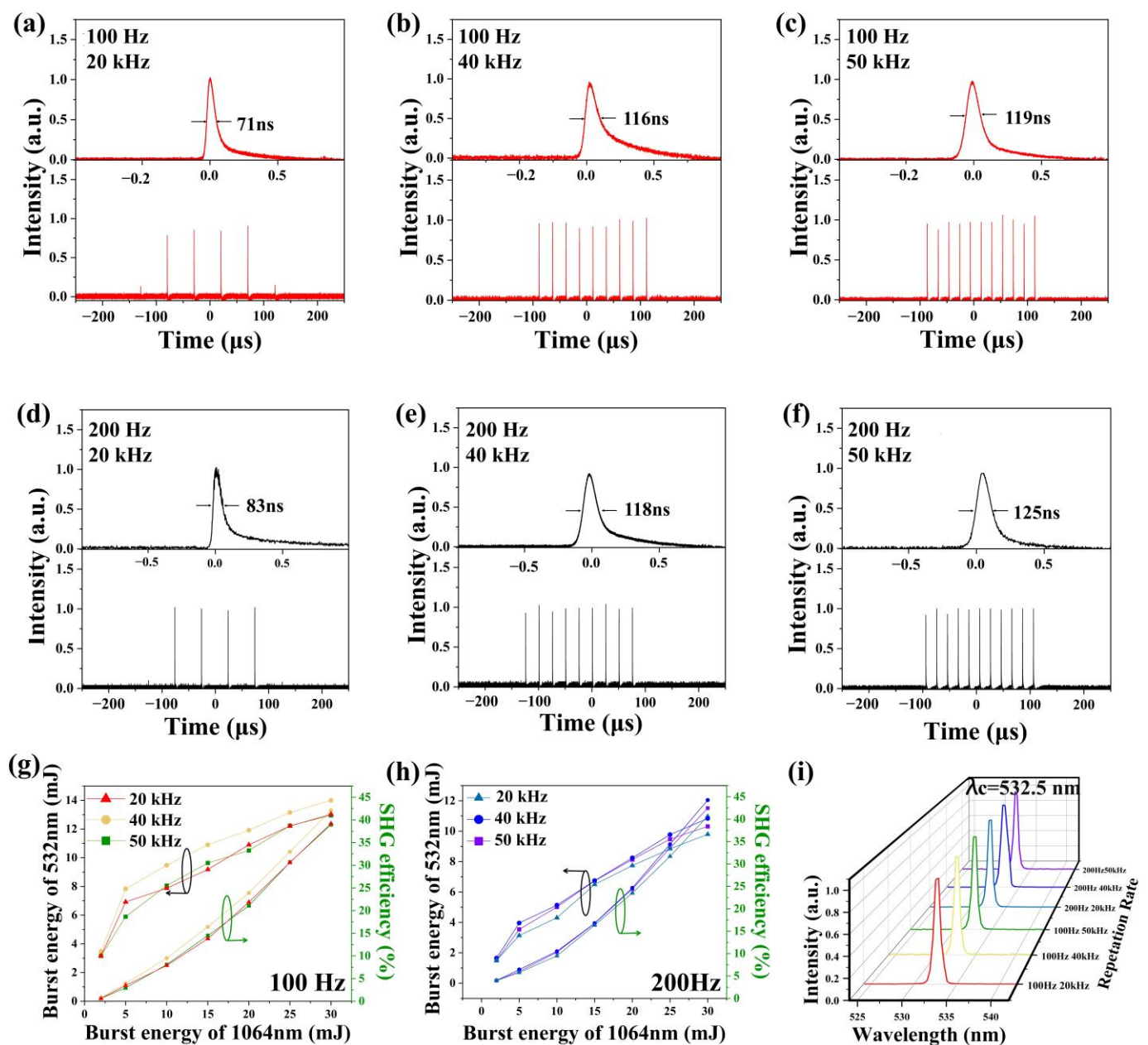


Figure 4. The single pulse profiles and pulse trains for 20 kHz, 40 kHz, 50 kHz sub-pulse repetition rates at burst repetition rate 100 Hz (a–c), 200 Hz (d–f); the output burst energy and SHG efficiency of 532 nm versus 1064 nm at different sub-burst repetition rates with burst repetition rate of (g) 100 Hz and (h) 200 Hz; (i) the spectrogram of the 532 nm output laser.

After passing through two nonlinear conversion crystals (LBO), the 1064 nm laser was frequency-tripled for the 355 nm ultraviolet (UV) laser. Similar to the 532 nm frequency-doubled laser, the 355 nm UV laser output maintained the same trend, with overall output energy and conversion efficiency at a 100 Hz pump repetition rate higher than that at 200 Hz. At sub-burst repetition rates of 20 kHz, 40 kHz, and 50 kHz, the output energies were 5.3 mJ, 5.3 mJ, and 5.1 mJ at 100 Hz, and 4.2 mJ, 4.4 mJ, and 3.7 mJ at 200 Hz. The corresponding conversion efficiencies were 17.7%, 17.7%, and 17% at 100 Hz, and 14%, 14.7%, and 12.3% at 200 Hz. As shown in the Figure 4d–f, the pulse width of the 355 nm laser was narrower than that of the 532 nm laser, decreasing from 71, 116, and 119 ns to 68, 102, and 110 ns at 100 Hz, and from 83, 118, and 125 ns to 79, 112, and 119 ns at 200 Hz. The output spectrum of the 355 nm laser is displayed in Figure 5i with a central wavelength of 355.3 nm. Figure 5a–f show the waveform profiles of the tripled 355 nm output pulses. The overall burst sequence of the tripled output exhibited a high degree of energy stability, and the high conversion efficiency confirms the feasibility of generating a 355 nm burst laser output.

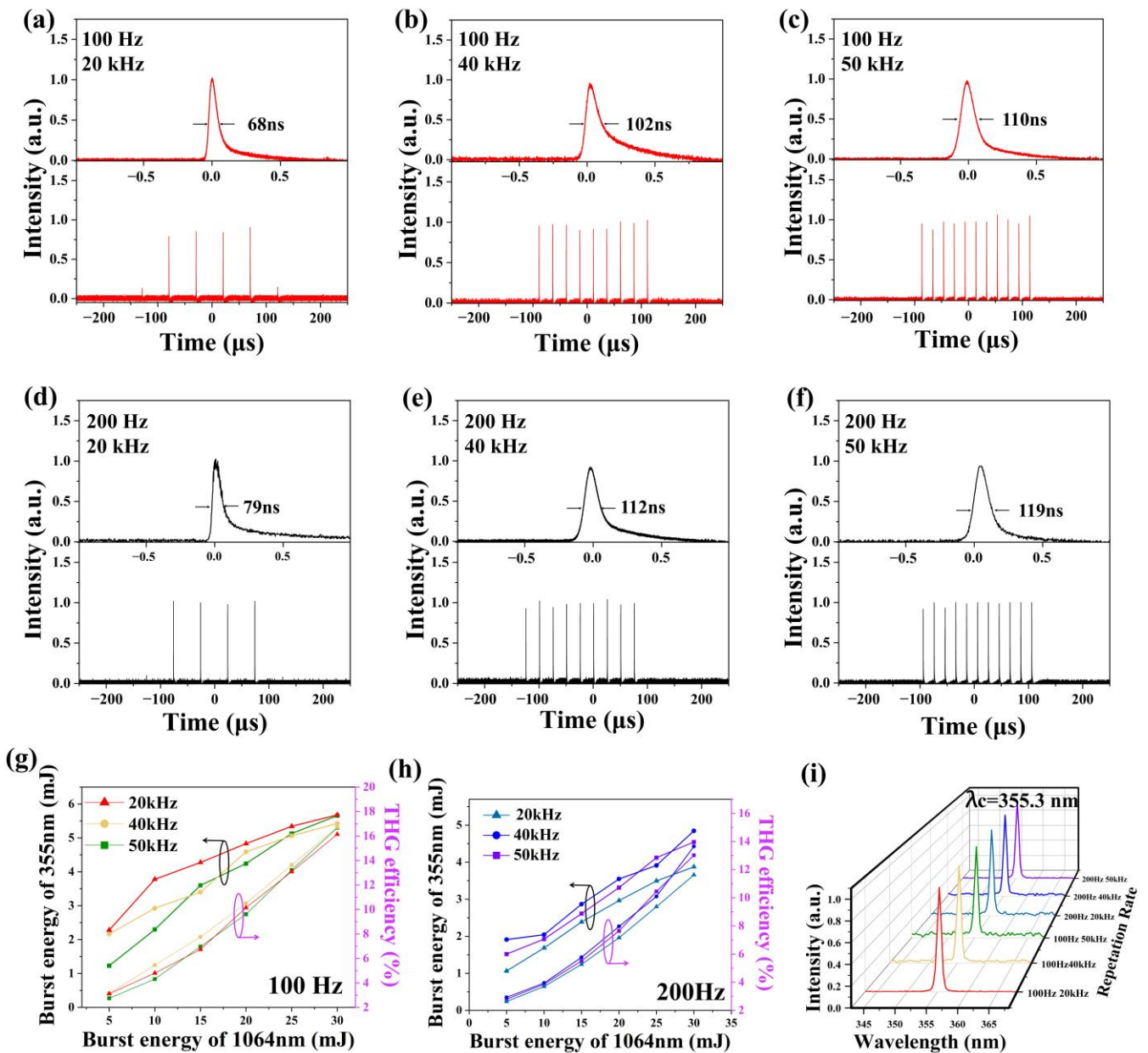


Figure 5. The single pulse profiles and pulse trains for 20 kHz, 40 kHz, 50 kHz sub-pulse repetition rates at burst repetition rate 100 Hz (a–c), 200 Hz (d–f); the output burst energy and THG efficiency of 355 nm versus 1064 nm at different sub-burst repetition rates with burst repetition rate of (g) 100 Hz and (h) 200 Hz; (i) the spectrogram of the 355 nm output laser.

At the maximum output energy of the 355 nm UV laser, we measured the laser beam quality factor M^2 , as shown in Figure 6. The M^2 values measured were 2.48 and 2.65 for 100 Hz, 3.83 and 3.95 for 200 Hz, for the horizontal and vertical axes of the output laser, respectively. The two-dimensional spatial intensity distributions of the laser beam are inserted in Figure 6a,b. It can be seen from Figure 6c–e, the pulse energy stability of 355 nm UV laser was measured to be 1.38%, 1.78% for 20 kHz, and 1.80%, 1.89% for 40 kHz, 2.24%, 1.86% for 50 kHz for 120 min.

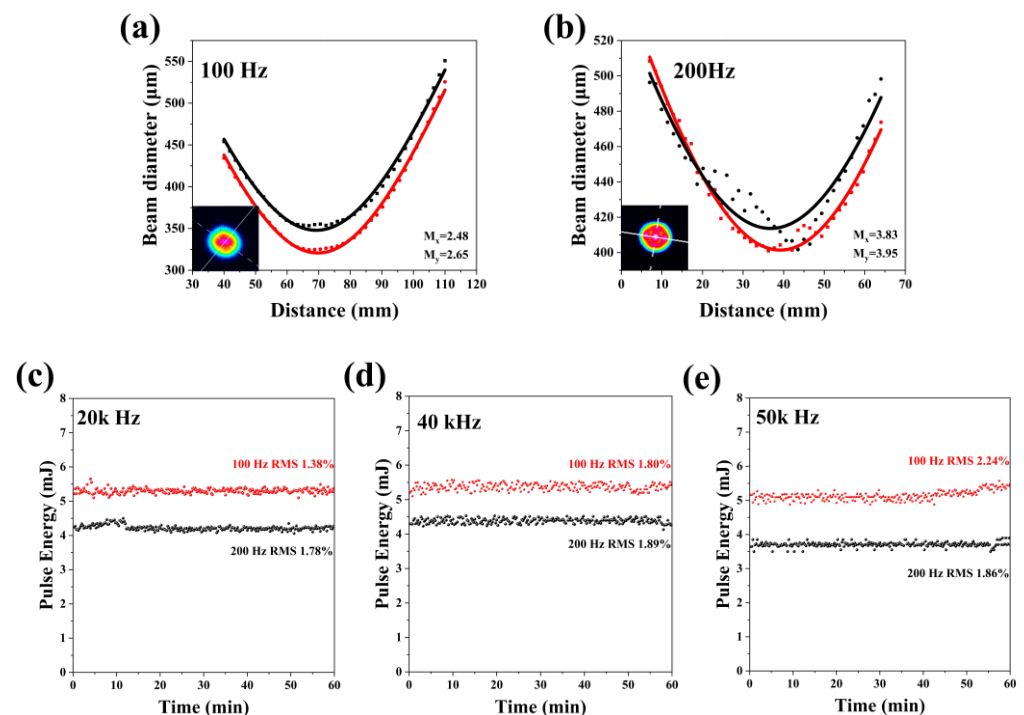


Figure 6. Beam quality and spatial intensity distribution for (a) 100 Hz and (b) 200 Hz at the highest energy of 355 nm UV laser; energy stability of 355 nm UV laser pulse for sub-burst repetition rate of (c) 20 kHz, (d) 40 kHz and (e) 50 kHz.

4. Conclusions

A frequency-tripled, high-energy, high-repetition-rate burst-mode 355 nm UV laser has been successfully demonstrated. Using burst-mode and electro-optical Q-switching technology, 30 mJ high-energy burst pulses at a fundamental wavelength of 1064 nm was achieved with diode-end pumped Nd: YAG crystal. The LBO nonlinear crystals were used for efficient second and third harmonic generation at sub-burst repetition rates of 20 kHz, 40 kHz, and 50 kHz. The 355 nm burst-mode UV laser output energies were 5.3 mJ, 5.3 mJ, and 5.1 mJ at 100 Hz, and 4.2 mJ, 4.4 mJ, and 3.7 mJ at 200 Hz. The corresponding conversion efficiencies were 17.7%, 17.7%, and 17% at 100 Hz, and 14%, 14.7%, and 12.3% at 200 Hz. The stable output at high energy suggests that this laser configuration was a promising choice for generating high-energy UV lasers with varying burst and sub-burst repetition rates, providing great potential for high-end processing of laser lift-off, annealing and slicing in display semiconductor field.

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C.J.; data curation, H.G. and C.J.; writing—original draft preparation, H.G. and J.Z.; writing—review and editing, H.G. and C.J.; visualization, B.Z.; supervision, J.H., J.X., and B.Y.; project administration, B.Z.; funding acquisition, H.N. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

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