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Frequency stabilization of an injection seeded Nd:YAG ring oscillator by ramp-fire technique with a $RbTiOPO_4$ modulator

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Abstract

We report on an injection seeded Q-switched Nd:YAG zigzag slab ring oscillator with pulse energy of 67 mJ and pulse duration of 19 ns at repetition rate of 20 Hz. With a $RbTiOPO_4$ (RTP) electro-optic crystal as the intra-cavity phase modulator, stable single frequency operation is achieved using the ramp-fire technique with a 10 μs linear voltage ramp sweeping 2.5 free spectral ranges. Frequency jitter of output pulse at 1064 nm is measured to be 2.0 MHz over 7 min. The beam quality factor is $M_x^2 = 1.38 \pm 0.03, M_y^2 = 1.29 \pm 0.02$ in seeded operation, which is improved from that of $M_x^2 = 1.67 \pm 0.01, M_y^2 = 1.35 \pm 0.01$ in free oscillation. The measured linewidth of the output is 27 MHz, which is 1.2 times Fourier-transformed-limited. Based on the RTP crystal as the modulator, the ramp-fire technique with a high ramp speed is capable of achieving high frequency and timing stability.

1 Introduction

Frequency stabilized high-power/energy lasers are required for many applications such as lidar remote sensing, spectroscopic analysis and nonlinear optics. Injection seeding has proven to be an effective and practical method of achieving stable single frequency operation of Q-switched lasers.

Successful injection seeding requires that the Q-switched slave oscillator is in resonance with the single frequency seed laser [1], which means the matching of both longitudinal and transverse modes of the two lasers. Several resonance-detection techniques, including the ramp-fire technique [2] and its modifications, are currently the most common cavity-control methods to maintain stable single frequency output.

The ramp-fire technique involves sweeping the optical length of the slave oscillator and then opening the Q-switch when the peak of the interference signal between two parts of the injected seed laser is detected. One part of the seed laser travels through one round trip of the cavity so the peak of the interference signal corresponds to the resonance condition. Drawback of the ramp-fire technique is that the Q-switch is opened at a random time due to the drift of the cavity length. Typical ramp time sweeping one spectral range is at dozens μs level, which equals the maximum jump in Q-switch firing time.

To settle this problem, the ramp-hold-fire technique [3] was introduced in which the voltage ramp is stopped when the peak is detected and held at the value until a fixed firing time. However, high-precision hold circuit operating in high speed and high voltage regime is difficult to achieve, which limits the use of ramp-hold-fire technique.

To improve the timing stability, another method is ramp-delay-fire technique [4]. A linear ramp voltage is applied sweeping at least two free spectral ranges. The first resonance peak is used as a pre-trigger and Q-switch is fired at a fixed delay (typically the time sweeping one spectral range). Only if the ramp is sufficiently linear can the firing time coincide with the second resonance peak. So nonlinearity is a source of frequency jitter in ramp-delay-fire technique.

Modulation of the optical length of the injected oscillator is usually implemented by a piezoelectric translator (PZT) modulator or an electro-optic modulator. In the former case, a cavity mirror which is mounted on a PZT is used. This approach suffers the following disadvantages: the driven speed of the PZT is slow; mechanical ringing caused by the inertia of the PZT introduces extra phase drift to the cavity length. In contrast, the use of the electro-optic modulator can eliminate these shortcomings. $RbTiOPO_4$ (RTP) crystal, being a very desirable material for Q-switches and

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electro-optic modulators, was used by Hovis et al. [5] as the phase modulator in injection seeded Q-switched Nd:YAG lasers. Because RTP exhibits no piezo-electric effect and high damage threshold, it is widely used in high energy lasers operating at high repetition rates.

In 2008, Hovis et al. [6] reported the ramp-fire technique in which a RTP intra-cavity phase modulator was driven by a 10 kHz sine wave. And a second control loop was used to stabilize the cavity length which reduced the timing jitter. In 2017, Lemmerz et al. [7] demonstrated both high frequency stability (0.25 MHz at 1064 nm) and high timing stability operation by a combination of the ramp-fire and ramp-delay-fire techniques. Cavity length was controlled by a PZT and the ramp time sweeping through one spectral range was at the level of 30 μs. Zhang et al. [8] reported the use of an RTP modulator with an ramp speed of about 40 μs/FSR realizing a frequency stability of 1.5 MHz over 2 min.

In this paper, to achieve both high frequency and timing stability in injection seeded single frequency Q-switched Nd:YAG oscillators, we focus on high frequency cavity modulation technique based on the intra-cavity phase modulator. With a RTP crystal as the modulator, the ramp-fire technique is investigated by using a linear voltage ramp with a much shorter rising time of 10 μs sweeping 2.5 free spectral ranges. Stable single frequency is obtained in a Nd:YAG zigzag slab ring oscillator with pulse energy of 67 mJ and pulse duration of 19 ns at repetition rate of 20 Hz. Frequency jitter at 1064 nm is measured to be 2.0 MHz over 7 min. Timing stability of the pulse is below 4 μs. Beam quality improvement is also observed when seeded, from $M_x^2 = 1.67 \pm 0.01, M_y^2 = 1.35 \pm 0.01$ in free oscillation to $M_x^2 = 1.38 \pm 0.03, M_y^2 = 1.29 \pm 0.02$ in seeded operation. And a 1.2 times Fourier-transformed-limited linewidth is achieved.

2 Laser system design

2.1 General

The experimental setup is shown in Fig. 1. The laser consists of the following main parts: a stable single frequency seed laser, optical coupling components, a Q-switched Nd:YAG zigzag slab ring oscillator, and a ramp-fire circuit.

The seed laser is a continuous-wave single frequency diode pumped monolithic nonplanar Nd:YAG ring oscillator (NPRO) with narrow linewidth and excellent frequency stability. Frequency drift of the seed laser was measured under laboratory conditions by a HighFinesse WSU-2 wavelength meter with an absolute accuracy of 2 MHz and a measurement resolution of 500 kHz. Short term frequency jitter of the seed laser is about 1 MHz/min. There is, however, a long term frequency drift of about dozens MHz over hours which is caused by the ambient temperature drift. The seed laser provides a maximum power of 1 W.

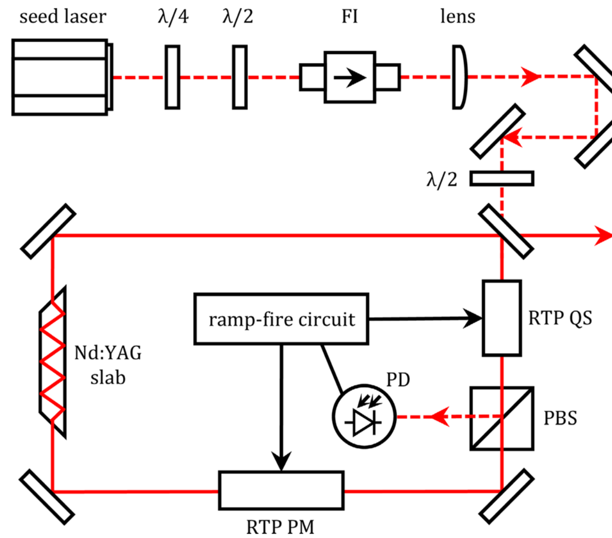

Fig. 1 Experimental setup of the laser. *λ/4* quarter-wave plate, *λ/2* half-wave plate, *FI* Faraday isolator, *RTP* $RbTiOPO_4$, *QS* Q-switch, *PBS* polarizing beamsplitter, *PM* phase modulator, *PD* photodiode

A Faraday isolator was used to prevent destabilization and damage of the NPRO seed laser by high energy pulses of the ring oscillator. As the output beam of the seed laser is elliptically polarized, it was transformed into the required linear polarization state by the combination of a quarter-wave plate and a half-wave plate before the isolator. To match the spatial modes of the seed laser and the ring oscillator, a focusing lens was used. It's focal length of 400 mm was elaborately chosen according to the beam waists of both the seed laser and the ring oscillator. In addition, the total optical length of injection was carefully measured. This way, both the beam radii and the longitudinal positions of the beam waists match. Transverse position of the seed laser's beam waist was adjusted through the 45° high reflectivity (HR) mirrors. To obtain the required polarization state of the seed laser, a half wave plate was inserted before injection.

The seed laser was injected into the ring oscillator through the output coupler mirror with a transmissivity of 50%.

Laser diode side pumped zigzag slab is one of most commonly used designs for high energy pulsed lasers. A 7-bounce, $4 \times 4 \times 54$ mm^3 Brewster-angle Nd:YAG slab was used as the gain medium. It was directly one-sided pumped on bounces by three 808 nm laser diode stacks with pulse duration of 250 μs at repetition rate of 20 Hz. The pumped surface of the slab was anti-reflective (AR) coated at 808 nm, and the opposite surface was HR coated because the pump light could not be fully absorbed by one passing through the 4 mm width of the cross section. Heat was removed from the top and bottom surfaces by a water-cooled copper heat sink.

The ring oscillator consists of 4 flat mirrors as a cavity. Its cavity length was 1 m, corresponding to a free spectral range of 300 MHz.

We chose the ring configuration resonator instead of standing wave resonator because it's more appropriate for single frequency operation by injection seeding. First of all, the ring cavity can eliminate the spatial hole burning effect, benefiting single longitudinal mode oscillation in contrast to the standing wave resonators. Second, the seed laser can be injected through the output coupler of the ring resonator to get a higher intra-cavity injected power. Moreover, in ring resonators, optical elements with low damage threshold can be placed at the lower laser intensity section.

However, because of the inherent travelling wave nature of the ring resonators, the voltages applied to the Q-switch and the phase modulator are twice higher than that in linear resonators.

With the thermally compensated design, a pair of $5\times5\times10$ mm^3 Y-cut RTP crystals was used as the Q-switch with a half wave voltage of 1700 V at 1064 nm. As in the ring-configuration resonator, full wave voltage of 3400 V was applied.

We also used RTP as the intra-cavity phase modulator, which is discussed in detail in the next subsection.

2.2 High speed ramp-fire technique with RTP modulator

The approach we use to maintain stable single frequency operation is the ramp-fire technique with RTP modulator. As mentioned above, freedom from piezo-electric ringing effect enables RTP to be driven at a higher speed. Consequently, a shorter ramp time can be applied.

A $5\times5\times40$ mm^3 RTP crystal was inserted as the intra-cavity phase modulator.

When the seed laser with a suitable polarization state was injected into the resonator, part of it was ejected from the PBS. After passing through one round trip of the cavity, it was ejected again. A photodiode was used to detect the interference signal between the two parts of seed laser. In order to reduce the drift of firing time, a high speed linear voltage ramp of 3 kV with a width of 10 μs was applied to the RTP modulator, sweeping the cavity through 2.5 free spectral ranges, and thus producing modulation on the interference. To detect the peaks of the interference signal and trigger the Q-switch, a ramp-fire circuit was made consisting of an amplifier, an analog to digital converter (ADC) and a field-programmable gate array (FPGA). Both the sample rate of the ADC and the clock frequency of the FPGA were set at 50 MHz.

Figure 2 illustrates the timing sequence of the ramp-fire circuit. The square wave of channel 1 in Fig. 2a is the pump current of LD with a pulse width of 250 μs. The rising edge

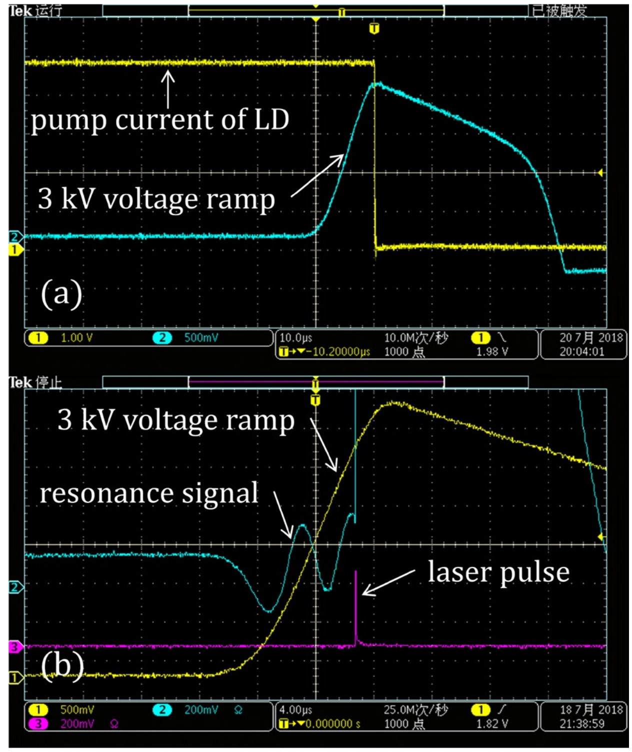

Fig. 2 Timing sequence of the ramp-fire circuit

of the pump current is not shown due to time scale. The 10 μs ramp voltage is applied 240 μs after the start of the pump. Thus, the ramp voltage and the population inversion reach their maximum simultaneously. Signal of channel 2 in Fig. 2b shows the resonance signal with 2 peaks. As a result of the thermal fluctuation and mechanical vibration of the environment, the initial phase of the resonance signal may drift randomly. Once the initial phase is close to the peak, the first peak may be missed. So we choose the second peak as the resonant condition to open the Q-switch.

3 Results and discussion

Signal of channel 3 in Fig. 2b shows the laser pulse after the second peak is detected. Q-switch could always be opened before the end of the pump. The pulse emission time drifted with a maximum jump of 4 μs because the peak separation was 4 μs.

Output energy of the ring oscillator in seeded and unseeded operation were measured as shown in Fig. 3.

Inherently, two counterpropagating traveling waves, both the clockwise (cw) and counterclockwise (ccw) waves, will produce an output in a ring oscillator. However, if one of the two modes has a slightly greater loss than the other, the output energy of the weaker one does not grow with increasing pump energy but reaches a constant value [9].

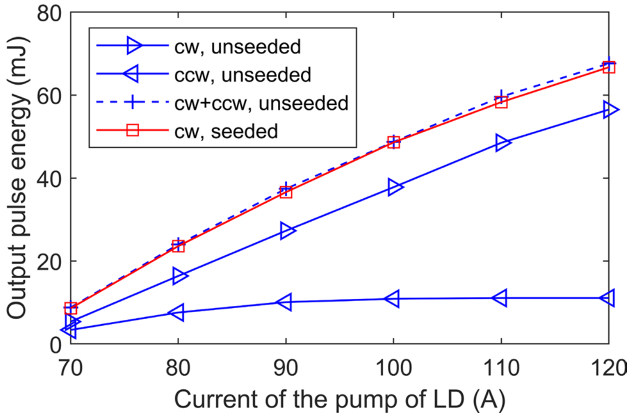

Fig. 3 Output energy of the ring oscillator in seeded and unseeded operation. *cw* clockwise, *ccw* counterclockwise

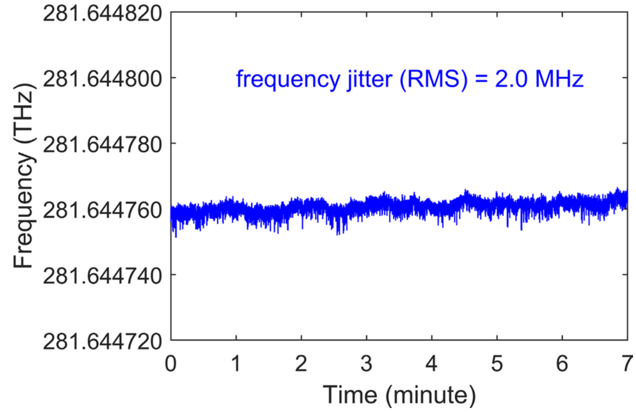

Fig. 4 Frequency stability of 1064 nm laser over 7 min (8400 shots)

In the laser shown in Fig. 1, as a result of the relative placement order of the RTP Q-switch and the PBS, the clockwise mode has a greater gain. The clockwise mode, therefore, dominates the output energy. As shown in Fig. 3, when unseeded, the output energy of the clockwise mode grows with increasing current of the pump laser diodes while the counterclockwise mode nearly reaches a constant value of about 11 mJ above current of 90 A.

However, when the ring oscillator was injected, an unidirectional output (the clockwise mode) was obtained. The output energy of the clockwise mode when seeded was equal to the total energy of clockwise and counterclockwise modes when unseeded, indicating that the counterclockwise mode is completely suppressed. In other words, injection seeding forces the ring laser to run unidirectionally. In the case of successful injection seeding, lasing occurs only in the same direction as the seed laser propagates.

Frequency stability of the 1064 nm laser was measured by the HighFinesse WSU-2 wavelength meter mentioned above under laboratory conditions.

Figure 4 shows the frequency drift in 7 min and the calculated frequency jitter (RMS) is 2.0 MHz.

Except for the ramp-fire technique, no other methods were used to stabilize the cavity length. The laser was built uncovered on an optical table without vibration isolators. The mechanical vibration mainly coming from the chiller resulted in the spikes in frequency. The ambient temperature of the laboratory was not controlled on purpose so slow thermal fluctuations was also a source of instability. The obtained frequency jitter is close to its lower limit which is the frequency stability of the NPRO seed laser.

To further improve the frequency stability, several measurements can be taken including vibration and temperature control of the ambient laboratory condition, improving the linearity of the ramp voltage and noise filtering of the ramp-fire circuit to improve accuracy of peak detection. Another cavity length control loop may be used to stabilize the frequency.

Injection seeding induced improvement of the beam quality was also observed.

Beam quality and spatial mode profile of both the NPRO seed laser and the ring oscillator were measured by an Ophir-Spiricon's M2-200s beam propagation analyzer. The value of M^2 was determined by the 90/10 knife edge method. The NPRO seed laser has a good beam quality with TEM_{00} mode and the measured M^2 was 1.1 in both two orthogonal axes. Without injection seeding, the clockwise mode of the ring oscillator with an energy of 56 mJ dominated the output and the beam quality factor was $M_x^2 = 1.67 \pm 0.01, M_y^2 = 1.35 \pm 0.01$ as shown in Fig. 5b.

When injection seeded, unidirectional operation of the ring oscillator was obtained and the clockwise energy increased to 67 mJ. The measured beam quality factor was $M_x^2 = 1.38 \pm 0.03, M_y^2 = 1.29 \pm 0.02$ as shown in Fig. 5d.

By injection seeding, there is an improvement of beam quality compared with that when unseeded. In previous works, beam quality improvement was observed in laser amplifiers [10, 11] and laser oscillators [12], but not ever in injection seeded lasers. Based on the theory of gain-thermal-guiding effect [10], the injected seed laser affects the thermal and gain distribution in crystal, causing the change of the focusing effect and then the beam quality. Consequently, the guiding effect in the injection seeded zigzag slab lasers may be the source of beam quality improvement. Further investigations will be made in our future works.

Experimentally, we observed the temporal output pulse shapes in seeded and unseeded operation. In Fig. 6, waveform (3) stands for the pulse shape without injection seeding when the clockwise output energy is 56 mJ. With injection seeding and the pulse energy of 67 mJ, waveform (1) is the pulse shape when in resonance while waveform (2) is the one when out of resonance.

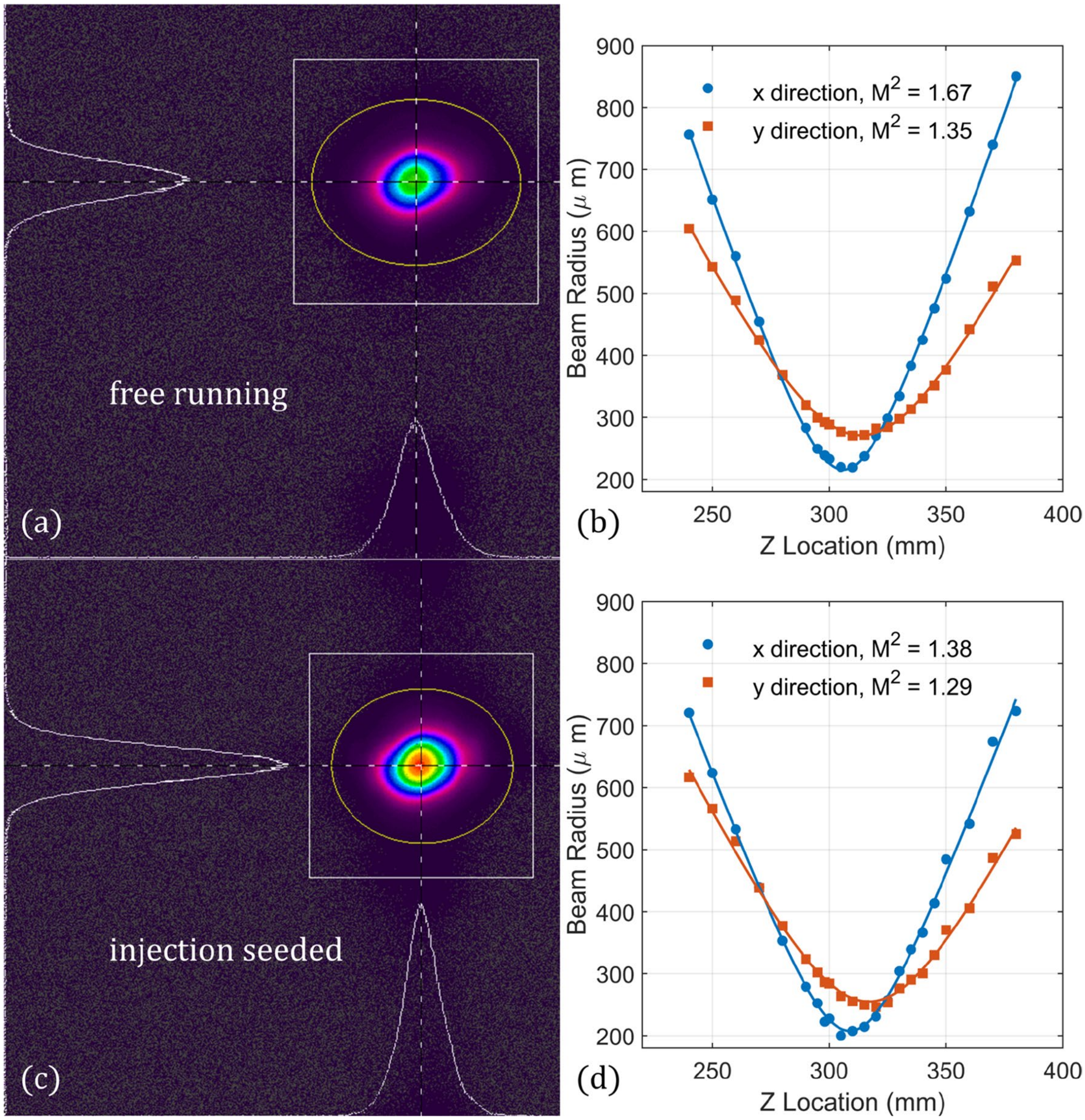

Fig. 5 Beam quality in seeded and unseeded operation. **a** Profile of laser output beam when unseeded; **b** measured beam quality factor when unseeded; **c** profile of laser output beam when seeded; **d** measured beam quality factor when seeded

Typically, the pulse shape of a free running ring oscillator shows strong distortion caused by longitudinal mode beating. While the ring oscillator is seeded but no measures are taken to match the frequencies of the two lasers, the pulse shape still shows modulations but at a lower modulation depth compared with the unseeded case. When the ramp-fire circuit is turned on, the distortion disappears and the pulse shows a smooth shape indicating a single longitudinal mode operation.

As for the build-up time of pulses, it decreases by 30–40 ns when seeded. Moreover, the shortest build-up time is reached in single frequency operation.

A scanning Fabry–Perot Interferometer (FPI, Thorlabs SA30-52) with a free spectral range of 1.5 GHz was used to measure the linewidth of the injection seeded single frequency output pulses. The wavelength range of the FPI is 488–532 nm. The finesse of the FPI is 1500, corresponding to a resolution of 1 MHz. The output pulses at 1064 nm with a pulse duration of 19 ns at the repetition of 20 Hz were first converted to the second harmonic at 532 nm by a KTP crystal, and then the linewidth was measured by the FPI with a slow scanning voltage.

The measurement result is shown in Fig. 7. During the 10 s scan time, several pulses were detected in each peak.

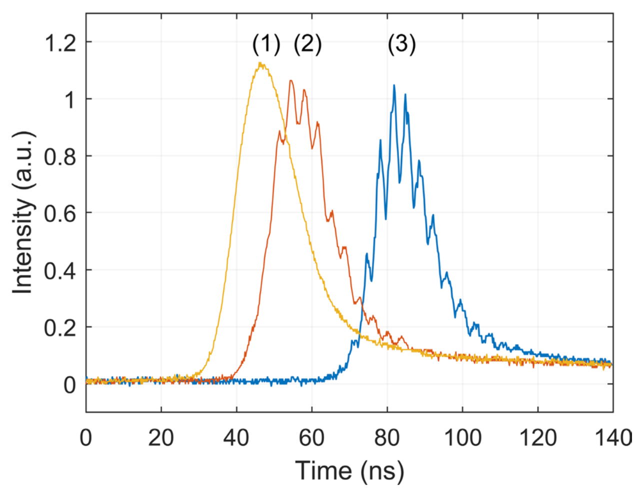

Fig. 6 Temporal pulse shapes of the clockwise output when the ring oscillator is **1** seeded and in resonance with the seed laser; **2** seeded but out of resonance with the seed laser; **3** unseeded

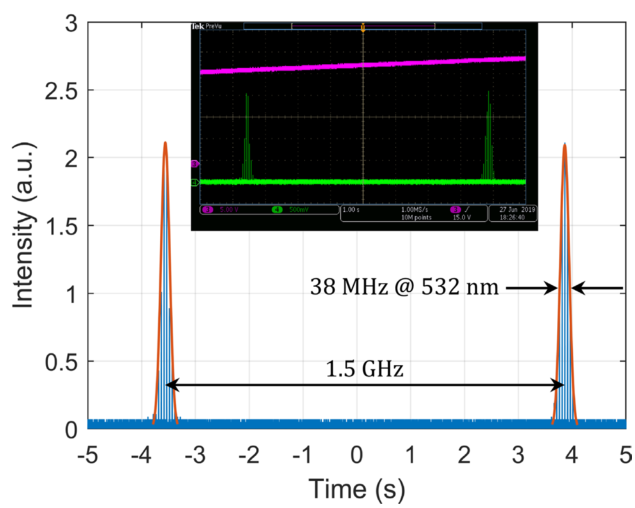

Fig. 7 The linewidth measurement of the injection seeded laser pulse at 532 nm taken with the FPI over a 10 s scan time. The FSR of the FPI is 1.5 GHz

The measured linewidth at 532 nm is approximately 38 MHz which corresponds to a 27 MHz linewidth at 1064 nm with a conversion factor of $1/\sqrt{2}$ assuming a Gaussian shape. The Fourier-transform-limited linewidth of a 19 ns Gaussian pulse is calculated to be 23 MHz [13]. As a result, a 1.2 times Fourier-transform-limited linewidth was obtained, revealing that injection seeding is an effective way of achieving narrow linewidth output in Q-switched lasers.

4 Conclusion

In conclusion, we demonstrate a stable single frequency operation of an injection seeded Q-switched Nd:YAG ring laser using the ramp-fire technique and an RTP intracavity phase modulator. Due to the excellent electro-optical properties of the RTP crystal, a much higher frequency modulation ramp voltage is applied with a speed of 4 µs/FSR. A frequency jitter of 2.0 MHz is obtained over 7 min. The drift of the absolute pulse emission time is less than 4 µs, and it can be reduced to below 1 µs by further increasing the ramp speed. The beam quality factor is $M_x^2 = 1.38 \pm 0.03, M_y^2 = 1.29 \pm 0.02$ in seeded operation, which is improved from that of $M_x^2 = 1.67 \pm 0.01, M_y^2 = 1.35 \pm 0.01$ in free oscillation. In addition, a 1.2 times Fourier-transform-limited linewidth is obtained.

Based on the electro-optic crystal as the modulator, the ramp-fire technique with a high ramp speed is capable of achieving both high frequency and timing stability. This method is especially applicable to injection seeded lasers operating at high repetition rates.

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References

1. Y.K. Park, G. Giuliani, R.L. Byer, IEEE J. Quantum Electron. **20**, 117–125 (1984)
2. S. Henderson, E. Yuen, E. Fry, Opt. Lett. **11**, 715–717 (1986)
3. T. Walther, M.P. Larsen, E.S. Fry, Appl. Opt. **40**, 3046–3050 (2001)
4. K. Nicklaus, V. Morasch, M. Hoefer, J. Luttmann, M. Vierkötter, M. Ostermeyer, J. Höffner, C. Lemmerz, D. Hoffmann, Proc. SPIE (2007). https://doi.org/10.1117/12.701187
5. F.E. Hovis, C. Culpepper, T. Schum, G. Witt, Proc. SPIE **5653**, 198–209 (2005). https://doi.org/10.1117/12.578771
6. F. Hovis, J. Edelman, T. Schum, J. Rudd, K. Andes, Proc. SPIE **6871**, 68710E (2008). https://doi.org/10.1117/12.768278
7. C. Lemmerz, O. Lux, O. Reitebuch, B. Witschas, C. Wührer, Appl. Opt. **56**, 9057–9068 (2017)
8. J. Zhang, X. Zhu, X. Ma, H. Zang, S. Li, S. Yin, W. Chen, Chin. Opt. Lett. **13**, 111404 (2015)
9. M.M. Tehrani, L. Mandel, Opt. Lett. **1**, 196–198 (1977)
10. X. Yan, Q. Liu, X. Fu, D. Wang, M. Gong, J. Opt. Soc. Am. B **27**, 1286–1290 (2010)
11. Z. Xiang, D. Wang, S. Pan, Y. Dong, Z. Zhao, T. Li, J. Ge, C. Liu, J. Chen, Opt. Express **19**, 21060–21073 (2011)
12. Y. Shen, M. Gong, X. Fu, Appl. Phy. B **124**, 85 (2018)
13. S.L. Shapiro, *Ultrashort light pulses: picosecond techniques and applications* (Springer, New York, 1997)