ISSN 1674-1056
http://cpb.iphy.ac.cn
http://iopscience.iop.org/cpb
中国物理 B
Chinese Physics
中国物理 Chinese Physics B

High-power ultraviolet 278-nm laser from fourth-harmonic generation of a Nd:YAG amplifier in CsB_3O_5crystal

Miao He(何苗), Feng Yang(杨峰), Cheng Dong(董程), Zhi-Chao Wang(王志超), Lei Yuan(袁磊), Yi-Ting Xu(徐一汀), Guo-Chun Zhang(张国春), Zhi-Min Wang(王志敏), Yong Bo(薄勇), Qin-Jun Peng(彭钦军), Da-Fu Cui(崔大复), Yi-Cheng Wu(吴以成), Zu-Yan Xu(许祖彦)
Citation: Chin. Phys. B . 2018, 27(5): 054212. **doi:** 10.1088/1674-1056/27/5/054211

Journal homepage: http://cpb.iphy.ac.cn; http://iopscience.iop.org/cpb

What follows is a list of articles you may be interested in

Er^{3+},Yb^{3+}:glass-Co^{2+}:$MgAl_2O_4$ diffusion bonded passively Q-switched laser

Yan Zou(邹岩), Yong-Ling Hui(惠勇凌), Jin-Lu Cai(蔡瑾鹭), Na Guo(郭娜), Meng-Hua Jiang(姜梦华), Hong Lei(雷訇), Qiang Li(李强)
Chin. Phys. B . 2017, 26(9): 094206. **doi:** 10.1088/1674-1056/26/9/094206

Design and performance of a composite Tm: YAG laser pumped by VBG-stabilized narrow-band laser diode

Shu-Tao Dai(戴殊韬), Jian-Hong Huang(黄见洪), Hai-Zhou Huang(黄海舟), Li-Xia Wu(吴丽霞), Jin-Hui Li(李锦辉), Jing Deng(邓晶), Yan Ge(葛燕), Wen-Xiong Lin(林文雄)
Chin. Phys. B . 2017, 26(7): 074211. **doi:** 10.1088/1674-1056/26/7/074211

Efficient Nd: YVO_4 laser in-band pumped by wavelength-locked 913.9-nm laser diode and Q-switch operation

Bin Li(李斌), Peng Lei(雷鹏), Bing Sun(孙冰), Yang-Bo Bai(白扬博)
Chin. Phys. B . 2017, 26(2): 024206. **doi:** 10.1088/1674-1056/26/2/024206

Design of LD in-band direct-pumping side surface polished micro-rod Nd:YVO_4 laser

Wen-Qi Zhang(张文启), Fei Wang(王飞), Qiang Liu(柳强), Ma-Li Gong(巩马理)
Chin. Phys. B . 2016, 25(2): 024207. **doi:** 10.1088/1674-1056/25/2/024207

Analytical model for thermal lensing and spherical aberration in diode side-pumped Nd:YAG laser rod having Gaussian pump profile

M H Moghtader Dindarlu, M Kavosh Tehrani, H Saghafifar, A Maleki
Chin. Phys. B . 2015, 24(12): 124205. **doi:** 10.1088/1674-1056/24/12/124205

Development of an injection-seeded single-frequency laser by using the phase modulated technique*

Shu-Tao Dai(戴殊韬)[1,2], Hong-Chun Wu(吴鸿春)[1], Fei Shi(史斐)[1], Jing Deng(邓晶)[1], Yan Ge(葛燕)[1], Wen Weng(翁文)[1], and Wen-Xiong Lin(林文雄)[1,2,†]

[1] *Key Laboratory of Optoelectronic Materials Chemistry and Physics, Fujian Institute of Research on the Structure of Matter, Chinese Academy of Sciences, Fuzhou* 350002, *China*

[2] *University of Chinese Academy of Sciences, Beijing* 100049, *China*

(Received 5 January 2018; revised manuscript received 29 January 2018; published online 26 April 2018)

An injection-seeded single-frequency *Q*-switched Nd:YAG laser is accomplished by using a phase modulated ramp-fire technique. A $RbTiOPO_4$ (RTP) electro-optic crystal is selected for effective optical path length modulation of the slave self-filtering unstable resonator. This single-frequency laser is capable of producing 50 mJ pulse energy at 1 Hz repetition rate with a pulse width of 16 ns. The standard deviation of laser pulse intensity for consecutive 100 shots from the mean pulse intensity is less than 1.05%. A spectral linewidth of less than 0.5 pm with a frequency jitter of about 14 fm over 30 min is obtained.

Keywords: single-frequency *Q*-switched Nd:YAG laser, injection seeding, phase modulation, self-filtering unstable resonator (SFUR)

PACS: 42.60.Gd, 42.60.Da, 42.60.By **DOI:** 10.1088/1674-1056/27/5/054212

1. Introduction

All-solid-state *Q*-switched single-frequency lasers are widely used in many fields, such as nonlinear optics, high-resolution spectroscopy and Doppler lidar.[1–4] Currently, injection seeding is one of the most frequently used techniques to produce single-axial-mode output from a *Q*-switched laser. It is achieved by injecting a low power narrow linewidth single-frequency seed laser into a *Q*-switched slave oscillator. If the seed laser has sufficient power, in the absence of spatial hole burning, the mode competition in the slave cavity will establish single-axial-mode oscillation.[5] However, the slave cavity must be in resonance with the frequency of the seed when the *Q*-switch of the slave cavity is activated. Hence, an active feedback locking system is required to ensure the resonance.

Schmitt and Rahn described a stabilization feedback locking technique by minimizing the *Q*-switched pulse build-up time (MBUT).[6] However, the feedback signal was obtained only once after each laser shot. This led to difficulties in certain situations such as low repetition rate operation and high noise environments. Fry *et al*. reported a ramp-fire locking technique for maintaining a single-frequency operation in severe environments based on fast resonance detection.[7,8] In this approach, optimum axial mode locking was achieved for each laser shot. This became the most reliable approach to realizing the stable single frequency operation. However, these techniques generally rely on a piezoelectric transducer (PZT) mounted on a cavity mirror to modulate the length of the cavity. However, the low time response of PZT limits the response rate of ramp system and the repetition rate of laser operation. The moving of the cavity mirror also results in unstability of the resonator. Zhang *et al*. demonstrated single-frequency output using a $LiNbO_3$(LN) crystal instead of PZT.[9] They obtained better spectrum performance by adopting LN compared with that by adopting the PZT.

In this work, we apply this intracavity phase modulation technique to a flashlamp-pumped Nd:YAG self-filtering unstable resonator (SFUR). There are several benefits in using the SFUR resonator. The SFUR resonator makes it easier for the laser to achieve seed injection mode matching and large mode volume. Finally, we obtain a high-energy, near-diffraction-limited TEM_{00} mode and stable narrow linewidth single-axial-mode pulse output.

2. Experiment design and setup

The geometry of the single-frequency laser is shown in Fig. 1. It is composed of a single-frequency seed laser, A *Q*-switched slave oscillator and a CPLD control circuit.

The seed laser is a commercial 1064 nm single-frequency laser (Mephisto S200NE, Coherent) with a spectral linewidth on the order of 1 kHz and maximum output power of 200 mW. The output light is elliptically polarized, and is transformed into linear polarization state by a quarter-wave and a half-wave plate. A Faraday isolator (IO-5-1064-VHP, Thorlabs) with an isolation of 40 dB is inserted behind the seed laser to prevent feedback from damaging by the *Q*-switched pulse.

*Project supported by the National Key Research and Development Program of China (Grant Nos. 2017YFB1104500 and 2016YFB0701000).

†Corresponding author. E-mail: wxlin@fjirsm.ac.cn

© 2018 Chinese Physical Society and IOP Publishing Ltd

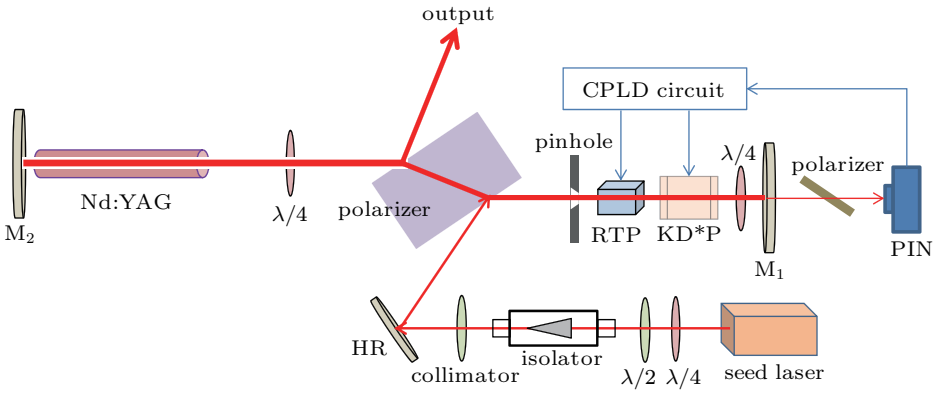


Fig. 1. (color online) Schematic diagram of The injection-seeded self-filtering unstable resonator.

The Q-switched slave oscillator is a flashlamp-pumped self-filtering unstable resonator (SFUR) Nd:YAG laser.[10] The SFUR configuration is a confocal negative branch unstable resonator. A field-limiting pinhole is located on the common focal plane of the cavity mirrors. The aperture is chosen such that a plane wave incident on it is focused by mirror M_1 on an Airy disk having the same diameter. Then this will result in the removal of the hot spot and the smoothing of the spatial profile. This yields

$$a = \sqrt{0.61\lambda f_1}, \tag{1}$$

where a is the aperture radius, f_1 is the focus of M_1 and λ is the laser wavelength. The Airy disk is only allowed to propagate beyond the aperture, and on reflection from the mirror M_2 it is magnified, collimated and presents a Fourier transformed output.[11]

A $RbTiOPO_4$ (RTP) crystal is used for intracavity optical path length modulation. The Y-cut RTP crystal has dimensions of $3(Z) \times 3(X) \times 20(Y)$ mm^3. The Z faces are plated with Ti electrodes onto which the modulating electric field is applied. The polarization of the input seed is parallel to the X-axis. In this case, the double pass effective optical path length change ΔL is given by

$$\Delta L = \gamma_{33} n_z^3 V \frac{L}{\lambda d}, \tag{2}$$

where L is the crystal length, d is the crystal thickness in the Z direction, n_z is the Z-axis refractive index and γ_{33} is the available electro-optic coefficient. Assume $L = 20$ mm, $d = 3$ mm, $n_z = 1.85$ and $\gamma_{33} = 35$ pm/V,[12] and ΔL will be about 1.06 μm for an applied voltage of 760 V. Then the seed transmitting the cavity will experience at least one resonant peak as the slave oscillator resonates with the seed laser. The interference signal is monitored by a photodiode detector (PDA10CS, Thorlabs) as shown in Fig. 2. After an appropriate time delay of the flashlamp pumping, the ramp voltage is triggered and applied to the RTP crystal. The interference signal is detected by monitoring the transmitted seed beam through the cavity mirror M_1 with a photodiode. The photodiode signal is sent to the CPLD circuit for detecting the peak and generating the Q-switched trigger signal.

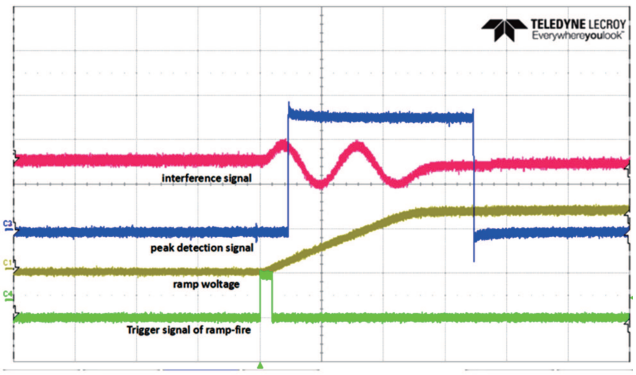


Fig. 2. (color online) Ramp voltage and interference signals with ramp-hold-fire technique.

3. Results and discussion

Figure 3 shows the variations of output energy from the laser with pump energy in the cases with and without seed injection. The pulse energy is reduced by 16% in the case with seed injection. This phenomenon due to inhomogeneous saturation gain broadening has been used as a new mode-locking technique called energy reduction (ER) by our group.[13]

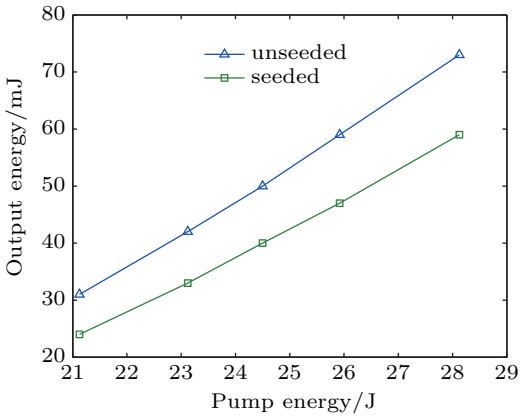


Fig. 3. (color online) Plots of output energy versus pump energy in the cases of the laser seeded and unseeded injection.

The beam spatial profile is shown in Fig. 4. A light divergence of 0.1 mrad is achieved. The SFUR configuration automatically produces a collimated output beam and smooth spatial profile. This is beneficial for the next amplifier, harmonic and optical parametric oscillator.

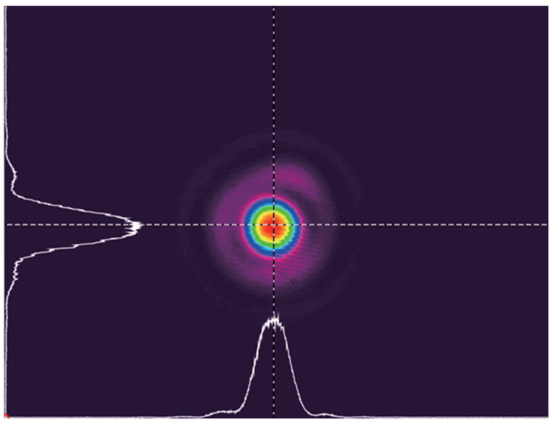


Fig. 4. (color online) Beam spatial profile of the laser.

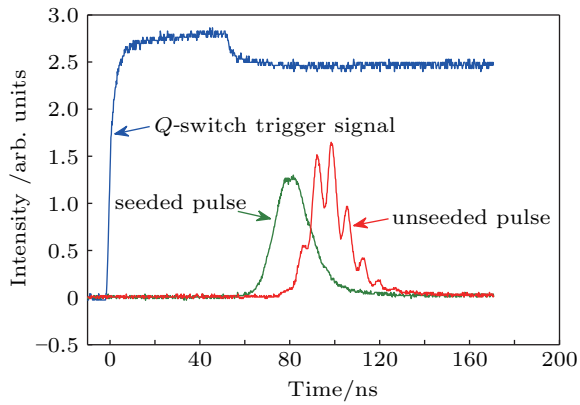


Fig. 5. (color online) Temporal profiles of the laser in seeded and unseeded operation, respectively.

The temporal shapes of the output pulse with seeded and unseeded injection are shown in Fig. 5. The pulse shape is measured by using a 1 ns rise time InGaAs photodiode (DET10A/M, Thorlabs) and a 1 GHz bandwidth oscilloscope (TELEDYNE MSO104MXs-B, Lecroy). The unseeded pulse shape shows strong modulation due to multimode beating. But the seeded pulse shows a smooth profile as expected for single-frequency operation. The build-up time of the seeded laser is reduced by 27.8 ns. The measured pulse width (FWHM) is around 16 ns at 50 mJ/pulse output energy.

The pulse energy stability is measured by measuring the area of the temporal profile of the laser pulse with the built-in function of the oscilloscope. The results shown in Fig. 6 indicate that the standard deviation (stdDev) of laser pulse intensity for consecutive 100 shots is less than 1.05% of the mean pulse intensity. The pulse width jitter is 183 ps (stdDev).

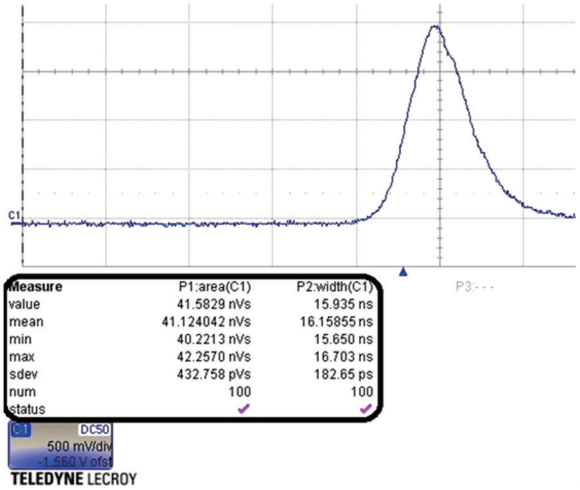


Fig. 6. (color online) Measured pulse energy and width of laser by oscilloscope.

The frequency spectrum of the seeded injection laser is further analyzed with a commercial Fizeau wavemeter (Angstrom WS/7, HighFinesse) as shown in Fig. 7. The linewidth is measured to be smaller than 0.5 pm, limited by the resolution of the measuring instrument. The wavelength is 1064.42840 nm. The frequency stability is also recorded by a wavemeter over 30 min, which is illustrated in Fig. 8. The frequency jitter is limited to 14 fm (stdDev). As a comparison, the frequency stability over 2 min is illustrated in the inset of Fig. 8 with 1.6 fm (stdDev).

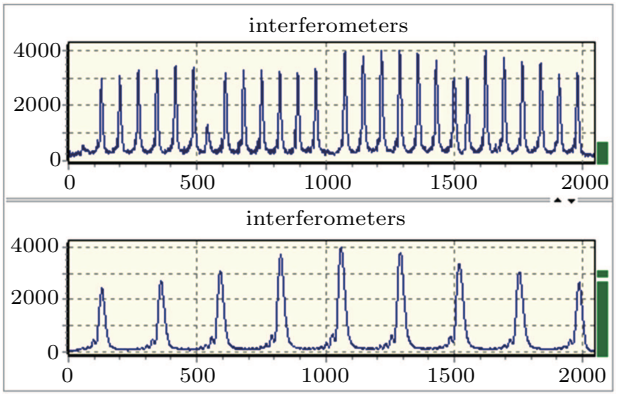


Fig. 7. (color online) Fizeau wavemeter interference pattern for the seeded injection laser. Upper and lower traces correspond to low and high-resolution Fizeau wedges, respectively. The horizontal axis shows the position of the interference signal (arb. units) and the vertical axis indicates relative intensity of the signal (arb. units).

However, the disadvantage of this laser is that the *Q*-switched firing time jumps randomly in one resonant cycle during the ramp, as shown in Fig. 9. Thus pulse-to-pulse fluctuation due to this jump results in the difficulty of synchronization and pulse energy fluctuation. Taking the advantage of fast no-ringing effect of the RTP crystal intracavity phase modulator, we demonstrate a modified ramp-hold-fire seed injection technique which can well solve this problem.

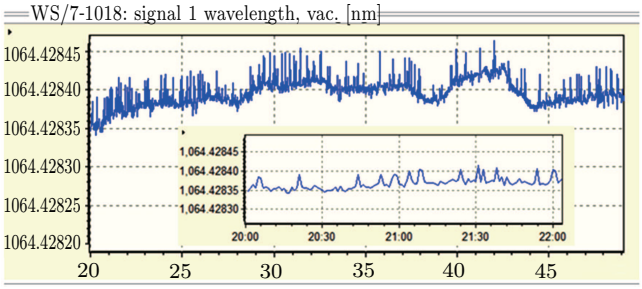


Fig. 8. (color online) Time behavior of the long-term frequency fluctuations recorded shot-to-shot over 30 min. The horizontal axis shows measurement time (min) and the vertical axis indicates measured wavelength (nm). The inset shows the same time behavior for two minutes.

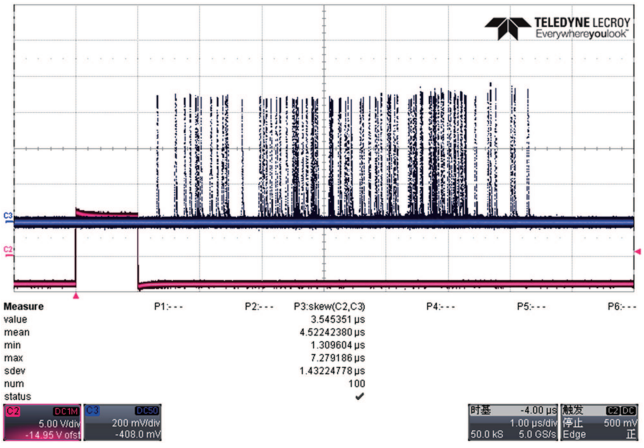


Fig. 9. (color online) Q-switched pulse drift with respect to the Q-switched firing time.

4. Conclusions

We have demonstrated a flashlamp-pumped Q-switched self-filtering unstable Nd:YAG single-frequency laser by using a phase-modulated ramp-fire technique. An RTP crystal is used for optical path length modulation. The single-frequency laser is capable of producing over 50 mJ pulse energy with a near-diffraction-limited spatial beam profile. The pulse duration is about 16 ns with a jitter of 183 ps, and the pulse-to-pulse energy stability is approximately 1%. The laser linewidth is measured to be less than 0.5 pm and the frequency stability is 14 fm over 30 min. The developed single frequency laser is scalable and harmonic, and is being incorporated into an OPO system.

References

[1] Kulatilaka W D, Anderson T N, Bougher T L and Lucht R P 2005 *Appl. Phys. B* **80** 669
[2] Liu J L, Liu Q, Li H, Li P and Zhang K S 2011 *Chin. Phys. B* **20** 312
[3] Kidd F G, Narayanaswamy V, Danehy P M, Inman J A, Bathel B F, Cabell K F, Hass N E, Capriotti D P, Drozda T G and Johansen C T 2014 30*th AIAA Aerodynamic Measurement Technology and Ground Testing Conference*, Jun 16–20, 2014, Atlanta, United States, paper AIAA 2652
[4] Zhang G X, Zhao Y F, Zhang Y C and Zhao P T 2008 *Acta Phys. Sin.* **57** 7390
[5] Koechner W 2006 *Solid-state laser engineering,* 6th edn. (New York: Springer) pp. 268–271
[6] Schmitt R L and Rahn R A 1986 *Appl. Opt.* **25** 629
[7] Henderson S W, Yuen E H and Fry E S 1986 *Opt. Lett.* **11** 715
[8] Fry E S, Hu Q and Li X 1991 *Appl. Opt.* **30** 1015
[9] Zhang J, Zhu X, Zang H, Ma X, Yin S, Li S and Chen W 2014 *Appl. Opt.* **40** 3046
[10] Bollanti S, Lazzaro P, Murra D and Zheng C E 2002 *Opt. Comm.* **209** 383
[11] Gobbi P G, Morosi S, Reali G C and Zarkasi A S 1985 *Appl. Opt.* **24** 26
[12] Roth M, Tseitlin M and Angert N 2005 *Glass Phys. Chem.* **31** 86
[13] Chen S, Lin W, Shi F, Huang J, Li J, Zheng H, Lin J and Xu C 2007 *Chin. Opt. Lett.* **5** 223