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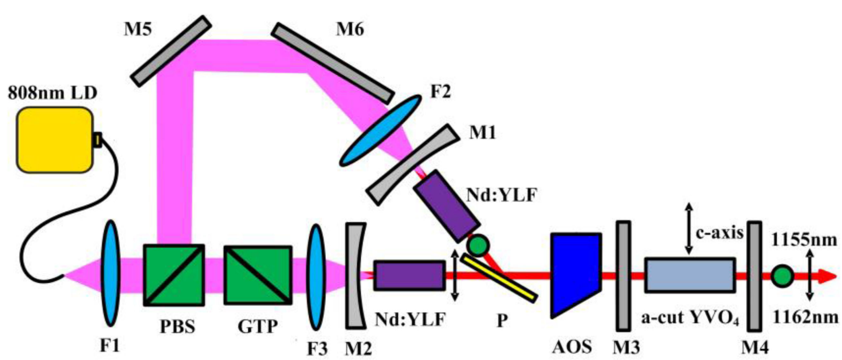


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# Multi-Watt Simultaneous Orthogonally Polarized Dual-Wavelength Pulse Generation of an Intracavity Nd:YLF/$YVO_4$ Raman Laser

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**Abstract:** We present the first demonstration of an actively Q-switched orthogonally polarized dual-wavelength Nd:YLF/$YVO_4$ Raman laser to our knowledge. The gain competition of the orthogonally polarized dual-wavelength fundamental laser at 1047 and 1053 nm was ultimately avoided by incorporating two Nd:YLF crystals into two laser resonators. By adjusting the gain or loss difference of two resonators, the pulse synchronization of the orthogonally polarized dual-wavelength Raman laser was realized. Benefitting from the efficient thermal stress and energy-transfer upconversion management of Nd:YLF crystal, a maximum dual-wavelength Raman output power of 4.5 W was obtained with $M^2 < 1.8$, which contained a 2.5 W Raman component at 1155 nm and a 2.0 W Raman component at 1162 nm, under the incident pump power of 46.1 W and pulse repetition frequency of 5 kHz. The corresponding peak powers were as high as 178.6 and 142.9 kW, respectively. As far as we know, we have increased the orthogonally polarized dual-wavelength Raman average output power by six times.

**Index Terms:** Raman conversion, diode end pumping, Q-switched lasers.

## 1. Introduction

Simultaneous orthogonally polarized dual-wavelength laser with a small wavelength separation has been of great interest in various applications, such as laser interference [1], precision metrology [2], differential Lidar [3], holography [4], and terahertz (THz) difference-frequency generation [5], [6]. Stimulated radiation based on the rare-earth-doped anisotropic laser medium has been validated as an efficient method to realize the orthogonally polarized dual-wavelength oscillation. However, due to the restriction of the energy level structure for the existing gain medium, the previous researches on the orthogonally polarized dual-wavelength lasers were mainly focused on several common wavelengths, including 0.9 [7], 1.0 [5], [6], [8]–[10], 1.3 [11], [12], and 2.0 $\mu$m [13]. In addition, the nonlinear frequency conversion technology, such as optical parametric oscillator (OPO) and stimulated Raman scattering (SRS), is another effective approach to extend the available spectral range of the orthogonally polarized dual-wavelength laser. By virtue of the dual-wavelength OPO technique, researchers have obtained the simultaneous orthogonally polarized dual-wavelength laser output at 1.5 and 2.0 $\mu$m [14], [15]. But OPO requires phase-matching and working near damage threshold for many nonlinear optical crystals, which make the system unstable and inconvenient [16]. Whereas SRS can realize automatic phase-matching without thermal dephasing compared with OPO, and provide beam quality improvement and pulse duration shortening compared with the fundamental laser radiation [17], [18].

In recent years, researchers have begun to investigate the orthogonally polarized dual-wavelength Raman lasers. In 2012, H. T. Huang et al. reported a simultaneous orthogonally polarized dual-wavelength laser at 1091 and 1095 nm by balancing the Raman gain of KTP and KTA, and the maximum average output power was 320 mW [19]. By introducing two Nd:YLF crystals into two laser cavities to generate the orthogonally polarized fundamental radiations, Y. Liu et al. obtained a 755 mW dual-wavelength Raman laser at 1159.4 and 1166.8 nm with a 46-mm-long $BaWO_4$ crystal in 2014 [20]. In 2016, Y. J. Sun et al. demonstrated a simultaneous orthogonally polarized multi-wavelength Yb:GAB/KGW intracavity Raman laser, which delivered two sets of dual-wavelength Raman lasers at 1133.1, 1156.6 nm and 1137.8, 1151.9 nm with the respective average output powers of 155 and 154 mW [21]. Unfortunately, the average output power of orthogonally polarized dual-wavelength Raman laser is still limited to watt-level up to now.

To improve the output performance of orthogonally polarized dual-wavelength Raman laser, laser medium and Raman medium should be carefully selected. As for anisotropic laser crystal, Nd:YLF has been recognized as a promising gain medium for the generation of high energy pulse laser due to its weak thermal lens effect and long upper-laser-level ($^4F_{3/2}$) lifetime ($\tau \sim 520$ $\mu$s) [22], [23]. However, the major drawbacks of Nd:YLF are its relative low thermal fracture and severe energy-transfer upconversion (ETU) effect, which limit its output power and beam quality [24], [25]. Reducing the Nd doping concentration of Nd:YLF and increasing the pump beam volume are reliable and attractive methods to increase the thermal fracture pump limit and reduce the ETU effect, which are beneficial to obtain a better output performance [25]–[27]. For Raman medium, $YVO_4$ was the most extensively researched and widely employed. Its Raman gain coefficient, damage threshold and thermal conductivity are comparable and even superior than the commonly known Raman crystals, such as $GdVO_4$, $BaWO_4$, $LiIO_3$, and $KGd(WO_4)_2$. Most importantly, $YVO_4$ is more readily available and inexpensive. Therefore, with the combination of Nd:YLF and $YVO_4$, a high- performance orthogonally polarized dual-wavelength Raman laser can be expected.

In this letter, we report on a multi-watt simultaneous orthogonally polarized dual-wavelength Raman pulse laser by employing Nd:YLF as the gain medium and economic $YVO_4$ as the Raman medium. Synchronizing the two Raman laser pulses at 1155 and 1162 nm was accomplished by modulating the gain or loss difference of two cavities. Combined with the advantages of the relative low Nd doping concentration and large pump beam size, the maximum average output powers at 1155 and 1162 nm were up to 2.5 W and 2.0 W at the pulse repetition frequency (PRF) of 5 kHz, respectively.

## 2. Experimental Details

The experimental configuration of the diode end-pumped actively Q-switched orthogonally polarized dual-wavelength Raman laser is illustrated in Fig. 1. The double-resonator structure was applied to generate two fundamental radiations at 1047 and 1053 nm with orthogonal polarizations ($\pi$ and $\sigma$). Two identical Nd:YLF crystals were placed at two divided arms decoupled by a polarizer (P). Therefore, the 1047 nm and 1053 nm fundamental lasers could achieve the population inversions from two separate laser crystals, which can alleviate the gain competition ultimately [6]. In our arrangement, the 1047 nm (s–polarized) and 1053 nm (p–polarized) lasers oscillated in the cavities

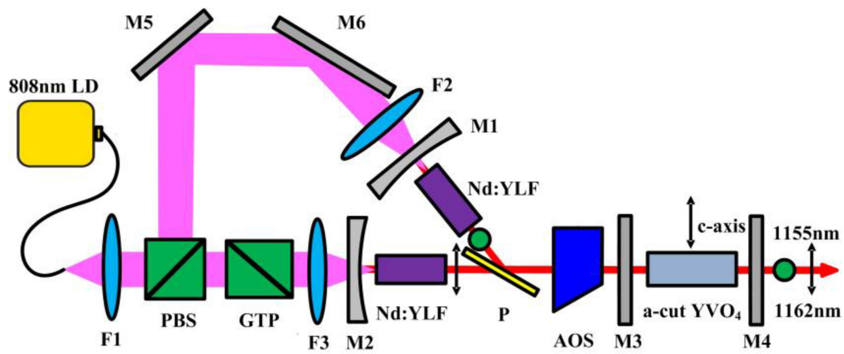


Fig. 1. Schematic of the simultaneous orthogonally polarized dual-wavelength intracavity Nd:YLF/YVO$_4$ Raman laser. PBS, polarizing beam splitter; GTP, Glan Taylor prism; AOS, acousto-optic Q-switcher.

with M1-P-M4 and M2-P-M4, respectively. The input mirrors (M1 and M2) were the plane-concave mirrors with radius-of-curvature of 300 mm coated for high transmission (HT) at 808 nm (T $>$ 98.5%) and high reflection (HR) at 1047–1053 nm (R $>$ 99.9%). The polarizer being placed at Brewster's angle (55.5$^o$) was coated for HT at the p–polarized (T $\approx$ 92%) and HR at the s–polarized (R $>$ 99.7%). A plane mirror (M4) coated for HR at 1047–1053 nm (R $>$ 99.9%) and partial reflectivity (PR) at 1155-1162 nm ($T_S = 10\%$) was chosen to be the Raman output coupler. The pump source was an 808 nm fiber-coupled laser diode (LD) with a core diameter of 200 $\mu$m and a numerical aperture (N.A.) of 0.22. With the aid of a polarizing beam splitter (PBS), the pump beam was tested to be unpolarized. The pump beam was collimated first by a lens F1 with a focal length of f $=$ 50 mm, and then divided into two branches by another PBS. Afterwards, the pump beam for 1047 nm cavity was reflected by two silver mirrors (M5 and M6) with HR coated at 808 nm (R $>$ 97.5%), and focused by a lens F2 with a focal length of f $=$ 250 mm into the Nd:YLF crystal of 1047 nm cavity. The remaining pump beam transmitted through the PBS was used to pump the Nd:YLF crystal of 1053 nm cavity after a lens F3 with a focal length of f $=$ 250 mm. Here, the Glan Taylor prism (GTP) was utilized to adjust the pump power level of 1053 nm cavity for achieving the pulse synchronization of dual-wavelength pulse laser. For two branches, the pump beams were re-imaged into the Nd:YLF crystals with a focus spot diameter of 1 mm. The 0.55 at.% a-cut Nd:YLF crystals with the dimension of $4 \times 4 \times 15$ mm$^3$ were coated for HT at 808 nm (T $>$ 99.5%) and 1047–1053 nm (T $>$ 99.3%) on the front surface, HR at 808 nm (R $>$ 94.7%) and HT at 1047–1053 nm (T $>$ 98.9%) on the other surface. The HR coated at 808 nm was used for improving the longitudinal gain uniformity, and ensuring a round-trip absorption efficiency of $\sim$92%. A 46-mm-long acousto-optic Q-switcher (Gooch & Housego, I-QS027-4S4G-U5-ST1) was placed at the shared arm of two laser cavities. The acousto-optic Q-switcher was driven at a 27.12 MHz ultrasonic frequency by a 100 W radio-frequency power. Flat intracavity mirror (M3) had a coating for AR at 1047–1053 nm (R $<$ 0.2%) on the entrance facet, and HR at 1155-1162 nm (R $>$ 99.9%) and HT at 1047–1053 nm (T $\approx$ 95%) on the other facet. So M3 and M4 made up the Raman laser cavity. An a-cut YVO$_4$ crystal with dimensions of $3 \times 3 \times 20$ mm$^3$ was selected to be the Raman gain medium, which was AR coated at 1047–1162 nm (R $<$ 0.1%) on both facets. Due to the relatively low stimulated emission cross section of Nd:YLF crystal at 1053 nm in $\sigma$-polarization compared with 1047 nm in $\pi$-polarization [28], so the c-axis of a-cut YVO$_4$ crystal was aligned parallel to the p-polarization of polarizer. During the experiment, all crystals were wrapped with indium foil and held in water-cooled copper heat sinks, and the water temperature was maintained at 18 °C. The physical lengths of both fundamental laser cavities and Raman laser cavity were 190 mm and 30 mm, respectively. According to the thermo-optical parameters of Nd:YLF crystal presented in [22], we estimated the average spot radii of the fundamental laser at the laser crystal and Raman cavity by using the ABCD matrix theory. Under the full incident pump power, the spot radii of the 1047 and 1053 nm TEM$_{00}$ modes were roughly calculated to be 345 and 360 $\mu$m at the Nd:YLF crystal as well as

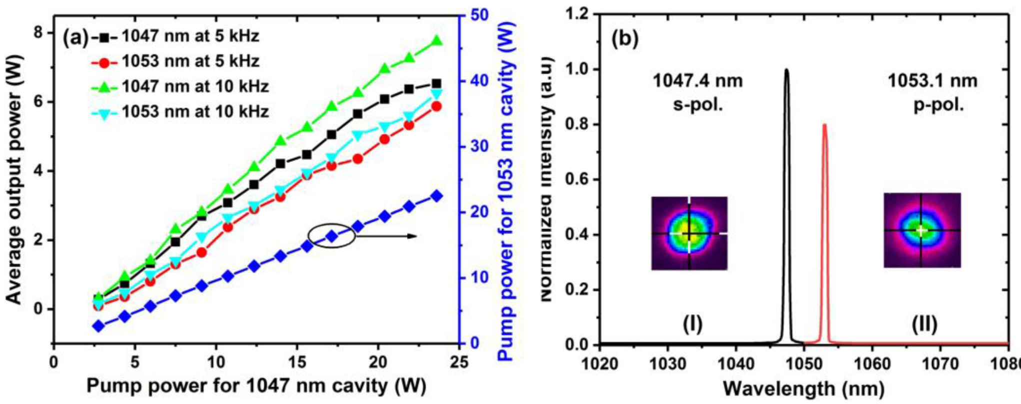


Fig. 2. (a) Average output powers at 1047 and 1053 nm as a function of the incident pump power at the PRFs of 5 and 10 kHz; (b) Spectrum of the dual-wavelength fundamental laser at the full output power, and the insets are the 2D beam intensity profiles at (I) 1047 nm and (II) 1053 nm.

255 and 210 $\mu$m in the Raman cavity, respectively. The output power was measured by an optical power meter (Physcience Opto-Electronics, LP-3C). The spectral information of the output laser was monitored by an optical spectrum analyzer (Zolix, Omni-$\lambda$300) with a resolution of 0.1 nm.

## 3. Experimental Results and Discussion

We first studied the output characteristics of the actively Q-switched orthogonally polarized dual-wavelength fundamental laser after removing the intracavity mirror and Raman crystal. A plane mirror with PR at 1047–1053 nm ($T_{OC} = 10\%$) was used as output coupler. According to the rate equation of a four-level laser system [29], the pulses' delay time can be adjusted by modulating the gain or loss difference of two cavities. This method has been proved to be effective in experiment [6], [20]. For this investigation, the time overlapping state of the dual-wavelength fundamental pulse laser was achieved for each pump power. Figure 2(a) depicts the average output powers at 1047 and 1053 nm with respect to the incident pump power at the PRFs of 5 and 10 kHz. It is noteworthy that the incident pump powers of 1047 and 1053 nm cavities refer to the respective detected pump powers before two input mirrors. We can see that the PRF has little influence on the pump power thresholds of two fundamental radiations, and the average output power at 10 kHz is higher than that at 5 kHz. The average output powers at 1047 and 1053 nm increased monotonously with the incident pump power. Under the incident pump powers of 23.6 W for 1047 nm cavity and 22.5 W for 1053 nm cavity, the maximum average output powers for 1047 and 1053 nm lasers were measured to be 6.5 and 5.9 W at 5 kHz as well as 7.7 and 6.3 W at 10 kHz, respectively. As a result, the maximum orthogonally polarized dual-wavelength fundamental laser average output power was up to 14 W with a net conversion efficiency of 30.4%. Compared with the previous result [6], we have improved the average output power at the same PRF by 2.6 times. Figure 2(b) presents the spectra of the dual-wavelength fundamental laser, where the emission wavelengths of $\pi$-polarization and $\sigma$-polarization are centered at 1047.4 and 1053.1 nm with the same full width at half-maximum (FWHM) of 0.9 nm. At the full output power, the spatial characteristics of the dual-wavelength fundamental laser was measured by using a laser beam analyzer (Spiricon, Inc. $M^2$-200s, 266–1125 nm). The laser beam quality factors $M^2$ for 1047 and 1053 nm lasers were found to be 2.0 and 2.4, respectively, and the corresponding far field two-dimensional (2D) beam intensity profiles are exhibited in the insets of Fig. 2(b).

Then, the output performance of the orthogonally polarized dual-wavelength Raman laser was investigated systematically. As similar to the fundamental laser operation, the pulse synchronization of the orthogonally polarized dual-wavelength Raman laser lines was also realized by mainly modulating the pump power level of two cavities. With the pulse synchronization maintained, we

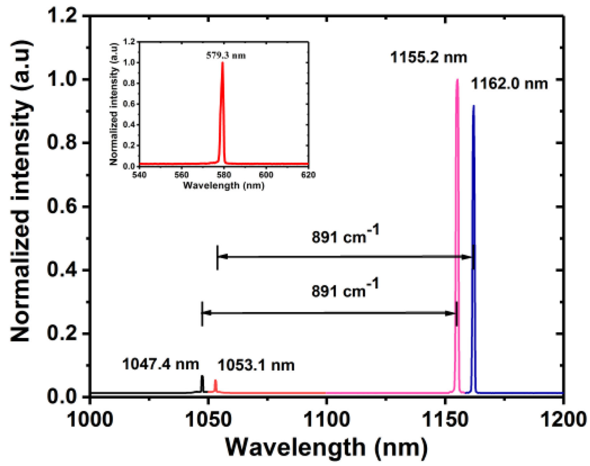


Fig. 3. Optical spectrum of the simultaneous orthogonally polarized dual-wavelength Raman laser at the full pump power, and the upper-left inset is the SFM spectrum of the two Stokes laser lines.

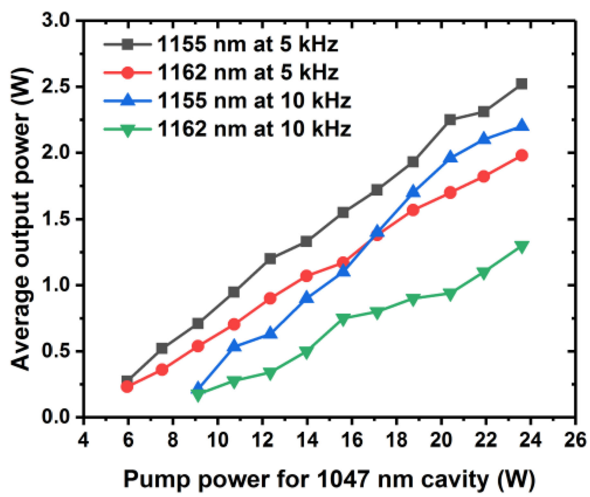


Fig. 4. Average output powers at 1155 and 1162 nm with respect to the incident pump power for 1047 nm cavity at the PRFs of 5 and 10 kHz.

found that the incident pump power ratio between 1053 nm cavity and 1047 nm cavity for operation was almost the same as fundamental operation. If the dual-wavelength Raman laser pulse has a bit out-sync, which can be resolved by slightly varying the angular tilt of two input mirrors. Under the pump power of 46.1 W, typical optical spectrum of the dual-wavelength Raman laser was registered after the output coupler M4, as shown in Fig. 3. The central wavelengths of the fundamental and first-Stokes dual-wavelength lasers were determined to be 1047.4, 1053.1 nm and 1155.2, 1162.0 nm, respectively. By using a cubic polarizer (Thorlabs, GL10-C), we found that the Raman lasers had the same polarization with the corresponding fundamental lasers. The frequency difference between 1147.4 and 1155.2 nm or between 1053.1 and 1162.0 nm is 891 $cm^{-1}$, which is in good agreement with the Raman shift of $VO_4^{2-}$-ionic groups [30]. The FWHMs of two Raman lines at 1155 and 1162 nm were 1.2 and 1 nm, respectively.

We measured the Raman output power after a dichroic mirror with HR coated at 1155–1162 nm and HT coated at 1047–1053 nm. Figure 4 shows the respective average output powers at 1155 and 1162 nm versus the incident pump power at the PRFs of 5 and 10 kHz. It can be seen from

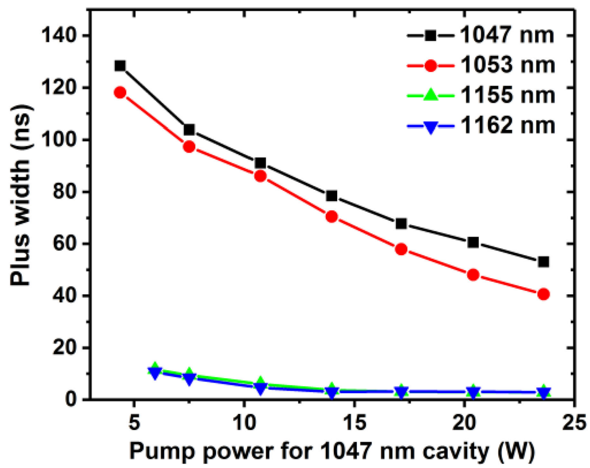


Fig. 5. Pulse widths of the four laser lines as a function of pump power for 1047 nm cavity at the PRF of 5 kHz.

Fig. 4 that the Raman threshold of the dual-wavelength Raman laser strongly relies on the PRF. A higher PRF led to a higher threshold, and the Raman thresholds at 5 and 10 kHz were 5.9 and 9.1 W, respectively. The Raman average output power at 5 kHz was higher than that at 10 kHz. Under the full incident pump powers of 23.6 W for 1047 nm cavity and 22.5 W for 1053 nm cavity, the maximum Raman average output power of 4.5 W was obtained at the PRF of 5 kHz, consisting of 2.5 W Raman output at 1155 nm and 2 W Raman output at 1162 nm, corresponding to a total optical power conversion efficiency of 9.8%. The power stabilities at 1155 and 1162 nm within one hour were found to be 3.9% and 2.6%, respectively. Due to the limitation of the spectral range of $M^2$-200s, the beam quality factor of dual-wavelength Raman laser was measured by using a knife-edge method. Under the maximum Raman output power, the $M^2$ factors of 1047 and 1053 nm lasers were found to be 1.7 and 1.8, respectively. The improved beam qualities of the dual-wavelength Raman laser could be mainly attributed to the beam cleanup effect of the SRS process [18]. As we know, we have improved the orthogonally polarized dual-wavelength Raman output power by nearly six-fold [20]. In addition, compared with [6] and 20, the two Nd:YLF crystals in divided cavities were successfully pumped by a LD in our experiment, which leads to a lower cost and simpler system. If the polarizer P has the higher transmission at the p–polarized, higher Raman output power can be expected. Integrating the benefits of the excellent thermal fracture management, no crystal fracture was observed. However, higher pump power was not adopted to prevent the optical film damage.

For the orthogonally polarized dual-wavelength fundamental and Raman operations, the respective pulse temporal characteristics at 5 kHz were recorded with a fast photodiode (Thorlabs, DET08CL/M) connected to an Agilent digital oscilloscope (DSO90604A, 6 GHz). As shown in Fig. 5, the pulse durations of the four laser lines decrease with the increasing incident pump power, and the pulse durations of 1047 and 1155 nm lasers are slightly broader than that of 1053 and 1162 nm lasers, respectively. In addition, the SRS process exhibited a significant pulse shortening compared with the fundamental beam [17]. At the maximum Raman output power, the pulse durations were measured to be 54.1, 42.8, 2.8, and 2.8 ns for 1047, 1053, 1155, and 1162 nm lasers, respectively. The corresponding peak powers of 1155 and 1162 nm lasers were calculated to be 178.6 kW and 142.9 kW, respectively.

Furthermore, under the full pump power of 46.1 W and PRF of 5 kHz, we simultaneously monitored the temporal behaviors of the orthogonally polarized dual-wavelength fundamental and Raman laser pulses after being separated with a PBS, as visualized in Fig. 6. The pulse-to-pulse amplitude stabilities at 1047 and 1053 nm as shown in Fig. 6(a) are evaluated to be better than $\pm$10.9% and

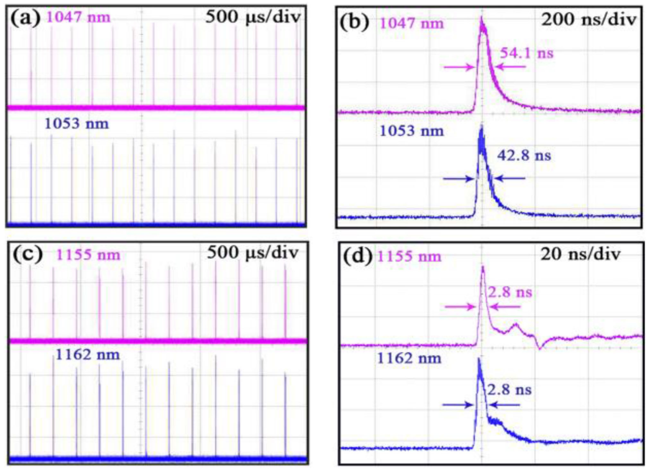


Fig. 6. Q-switched laser pulse train and temporally expanded single pulse profiles of the (a) fundamental and (b) Raman dual-wavelength laser pulses at the full pump power of 46.1 W and PRF of 5 kHz.

±12.3%, respectively. The large instability of the fundamental laser pulse train could be introduced by two reasons. One is the beating frequency of the high order transverse mode. The other reason is that the AQS can't be completely turned off under the full incident pump power. In addition, the results from Fig. 6(b) indicate that there is no time delay between the 1047 and 1053 nm fundamental lasers. For the dual-wavelength Raman laser, the pulse-to-pulse amplitude stabilities at 1155 and 1162 nm were experimentally found to be better than ±12.6% and ±11.9%, respectively, as depicted in Fig. 6(c). Moreover, the time overlapping state of the two Stokes lasers at 1155 and 1162 nm was also as displayed in Fig. 6(d). To further verify the synchronization of two Stokes lasers, we performed the extra-cavity sum frequency mixing (SFM) experiment with an 8-mm-long type-II phase-matched KTP crystal ($\theta = 70.5°$, $\phi = 0°$). The SFM spectrum is shown in the upper-left inset of Fig. 3, and the result illustrates that the two Stokes laser lines are synchronized.

## 4. Conclusions

In summary, a simultaneous actively Q-switched orthogonally polarized dual-wavelength intracavity Nd:YLF/$YVO_4$ Raman laser at 1155 and 1162 nm has been demonstrated for the first time. Under the incident pump power of 46.1 W, the maximum Raman average output power of 4.5 W was achieved at the PRF of 5 kHz, which comprised a 2.5 W 1155 nm Raman laser and a 2.0 W 1162 nm Raman laser. The corresponding pulse widths for both wavelengths were found to be 2.8 ns, and the pulse peak powers were calculated to be 178.6 kW and 142.9 kW, respectively. At the full output power, the $M^2$ factors of two Stokes radiations were measured to be better than 1.8. This result represents a significant improvement in terms of the average output power and pulse peak power over previously reported results. Combined with the advantages of the most economic $YVO_4$ crystal and low-cost pumping system, such a high-performance laser source could be of particular significance in many applications, such as laser interferometry, precision metrology, and the generation of visible and THz radiation.

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