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Multi-wavelength continuous-wave Nd:YVO_4 self-Raman laser under in-band pumping*

Li Fan(樊莉)†, Xiao-Dong Zhao(赵孝冬), Yun-Chuan Zhang(张蕴川), Xiao-Dong Gu(顾晓东), Hao-Peng Wan(万浩鹏), Hui-Bo Fan(范会博), and Jun Zhu(朱骏)

College of Physics Science and Technology, Institute of Applied Photonic Technology, Yangzhou University, Yangzhou 225002, *China*

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Multi-wavelength continuous-wave self-Raman laser with an *a*-cut composite YVO_4/Nd:YVO_4/YVO_4 crystal pumped by an 879-nm wavelength-locked laser diode is demonstrated for the first time. Multi-wavelength Raman lasers at 1168.4, 1176, 1178.7, and 1201.6 nm are achieved by the first Stokes shift of the multi-wavelength fundamental lasers at 1064, 1066.7, 1073.6, 1084, and 1085.6 nm with two Raman shifts of 890 and 816 cm^{-1}. A maximum Raman output power of 2.56 W is achieved through the use of a 20-mm-long composite crystal, with a corresponding optical conversion efficiency of 9.8%. The polarization directions of different fundamental and Raman lasers are investigated and found to be orthogonal π and σ polarizations. These orthogonally polarized multi-wavelength lasers with small wavelength separation pave the way to the development of a potential laser source for application in spectral analysis, laser radar and THz generation.

Keywords: multi-wavelength, continuous-wave, self-Raman laser, in-band pumping

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1. Introduction

All-solid-state lasers emitting at multi-wavelength simultaneously have attracted great attention because of their important applications, such as in spectroscopy, laser probe, differential radar, and especially terahertz wave (THz) generation.[1–3] So far, various crystals doped with Nd^{3+}-ions (Nd:YVO_4, Nd:YAG, *etc*.) have been employed as the laser gain media for dual- or multi-wavelength fundamental laser generation.[4–9] In addition, stimulated Raman scattering (SRS) in the solid-state crystals have recently been used to generate multi-wavelength emission in both pulsed (Q-switched)[10–13] and continuous-wave (CW) regimes.[14–19] Compared with fundamental lasers, Raman lasers have the advantages of high beam quality, short pulse duration, and pure spectrum.[20,21]

In the CW Raman laser, the Raman conversion efficiency is very sensitive to the thermal effect and cavity loss. As reported in Ref. [19], a multi-wavelength CW Yb:YAG/Nd:YVO_4 microchip Raman laser was demonstrated by reducing the thermal effect and cavity loss. The maximum Raman output power of 260 mW at 1.08 μm was achieved and the corresponding optical conversion efficiency was 4.2%. Besides the microchip Raman lasers, the self-Raman laser is another promising configuration due to its compactness and lower resonator loss. The Nd:YVO_4 crystals have been widely used in self-Raman lasers due to their excellent laser and Raman properties. According to its emission spectrum,[6,22] the Nd:YVO_4 crystal can generate different fundamental laser wavelengths in π and σ polarizations. The emission peaks are located at 1064, 1073, and 1085.5 nm in π polarization ($E \parallel c$), while for σ -polarization ($E \perp c$), the peak emission wavelengths are 1062.6, 1064.4, 1066.2, and 1083.3 nm, respectively. In addition, as reported in Ref. [23], YVO_4 crystal has several Raman shift peaks of 890, 838, 816, 376, and 259 cm^{-1} for different polarized pumps. Given these characteristics, it is easy to obtain multi-wavelength laser radiation in Nd:YVO_4 self-Raman laser. For instance, in 2013, Li *et al.* reported a CW multi-wavelength *a*-cut Nd:YVO_4 self-Raman laser based on the 1064 nm fundamental laser and two Stokes shifts of 893 and 379 cm^{-1}.[15] The maximum output powers of 1.0 W, 700 mW, and 540 mW were obtained at 1109 nm, 1158 nm, and 1231 nm respectively. In 2016, Lin reported a pulsed multi-wavelength *c*-cut Nd:YVO_4 self-Raman laser, in which the fundamental laser at 1066.8 nm was transferred into the multi-wavelength Raman lasers with Stokes shifts of 890, 816, and 261 cm^{-1}.[11] In these studies, the multi-wavelength Raman lasers were obtained by using different or cascaded Raman shifts from a single wavelength fundamental laser. Shayeganrad only demonstrated a dual-wavelength (1178.9 nm and 1199.9 nm) *c*-cut Nd:YVO_4/YVO_4 Raman laser based on a dual-wavelength (1066.7 nm and 1083.9 nm) fundamental laser in 2013.[24] Note that these laser lines have the same polarization.

In addition, it is worth mentioning that thermal loading

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†Corresponding author. E-mail: fanli@yzu.edu.cn

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of self-Raman crystal is more severe, which limits the Raman output power. As we have known, in-band pumping is an efficient approach to reducing thermal effects. However, for the Nd:YVO_4 crystal, relatively weak absorption at 880 nm restrains the improvement of conversion efficiency. In 2014, the wavelength-locked in-band pumping LD was introduced into Q-switched self-Raman lasers by Sheng *et al.*[25] and Ding *et al.*[26] Because the narrow-linewidth emission of pump source matched accurately to the in-band pumping absorption peak of laser crystal, pump absorption was improved and simultaneously thermal effect was reduced. Therefore, higher optical conversion efficiency could be obtained than what the common 880-nm pumping and traditional 808-nm pumping could achieve.

In this paper, we report a simple and compact multi-wavelength CW self-Raman laser with a composite YVO_4/Nd:YVO_4/YVO_4 crystal end-pumped by a wavelength-locked laser diode at 879 nm. To the best of our knowledge, multi-wavelength laser operation simultaneously around 1.06-μm fundamental laser and 1.18-μm first Stokes laser in an *a*-cut Nd:YVO_4 crystal is obtained for the first time. Output spectrum is abundant which includes the fundamental lines at 1062.8, 1064, 1066.7, 1073.6, 1084, and 1085.6 nm and the first Stokes lines at 1168.4, 1174, 1176, 1178.7, 1199.7, and 1201.6 nm. This phenomenon is a result of using the wavelength-locked laser diode at 879 nm and long composite crystal, which reduce thermal effect and meanwhile improve the pump absorption and Raman gain. Finally, a total output power of first-Stokes laser, up to 2.56 W, is achieved at an incident pump power of 26 W, corresponding to an optical conversion efficiency of $\sim 9.8\%$. The polarizations of different fundamental lasers are investigated and found to be orthogonal π and σ polarizations. The same phenomenon was observed in different Raman lasers, which are found to be orthogonally polarized.These wavelength lasers prove to be a significant supplement to the previous self-Raman Nd:YVO_4 laser at 1176 nm and have potential applications in spectral analysis, laser radar and THz generation.

2. Experimental setup

The experimental configuration of a CW multi-wavelength Nd:YVO_4 self-Raman laser is shown in Fig. 1. The pump source was a wavelength-locked 879-nm fiber-coupled laser diode (nLIGHT, Inc.) with a maximum output power of 30 W, core diameter of 200 μm and numerical aperture of 0.22. We measured the output spectra of the LD at different temperatures and output powers and found that the peak emission wavelength was locked at 879 nm with a narrow linewidth (< 0.3 nm FWHM), which matched well with the absorption peak of Nd:YVO_4 around 880 nm.[25] So the use of this pump source mitigates the thermal effect and at the same time improves pump absorption. Three *a*-cut Nd:YVO_4 crystals (Crystech, Inc.) were evaluated: one was a conventional 0.3-at.% doped Nd:YVO_4 crystal with dimensions 4 mm×4 mm× 10 mm, and the other two were double-end diffusion-bond Nd:YVO_4 composite crystals (YVO_4/Nd:YVO_4/YVO_4) with dimensions 4 mm×4 mm×14 mm and 4 mm×4 mm×20 mm, in which 0.3-at.% Nd:YVO_4 was bounded by 2-mm-long pure YVO_4 at the two light-passing facets to mitigate thermal effects. In order to reduce the cavity loss and obtain multi-wavelength laser output, both end faces of crystals were antireflection (AR) coated at 800 nm–1600 nm ($R < 5\%$@880 nm, $R < 0.5\%$@1064 nm, $R < 0.2\%$@1176 nm). The crystals were wrapped with indium foils and mounted in water-cooled copper blocks with water temperature maintained at 18 °C. The pump beam was refocused into the Nd:YVO_4 crystal by a commercial 1:2 coupler, which results in the diameter of the pump beam in the crystal being ~ 400 μm.

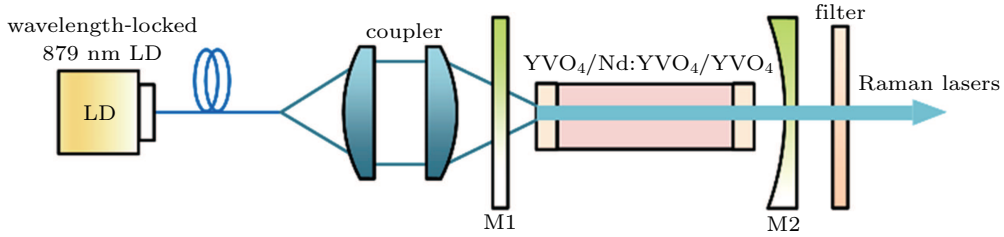


Fig. 1. Arrangement of wavelength-locked 879-nm laser diode end pumped composite YVO_4/Nd:YVO_4/YVO_4 CW self-Raman laser.

The input mirror M1 was a flat mirror and the M2 represented different concave output couplers with different radii of curvature (50, 100, 200, 300, 500, and 800 mm). All mirrors were coated with high transmission at 880 nm ($T > 99\%$) and high reflectivity at 1063 nm–1202 nm. The reflectivities were 99.89%, 99.90%, and 99.91% at fundamental wavelengths of 1063 nm–1066 nm, 1074 nm, and 1084 nm–1086 nm, and 99.83%, 99.8%, and 99.6% at Raman laser wavelengths of 1168.4 nm, 1174 nm–1178 nm, and 1200 nm–1202 nm, respectively. In the experiment, all the resonator elements were placed as close as possible to minimize the resonator length, which varied from 17 mm (for the 10 mm and 14 mm long crystals) to 23 mm (for the 20 mm long crystal). A longpass filter (FEL1100 Thorlabs) and a bandpass filter (FLH1064-8

Thorlabs) were used to separate the output beam of the fundamental laser from that of the Raman laser. The output power was measured by a laser power meter (LP-3B) and the output spectra were recorded by an optical spectrum analyzer with a 0.02-nm resolution (Yokogawa, AQ-6370 C).

3. Results and discussion

The performance of the self-Raman laser system is investigated with the three Nd:YVO_4 crystals and several output couplers with different radii of curvature (50, 100, 200, 300, and 500 mm). The highest Raman output power is obtained when the 20-mm-long composite crystal and a 100-mm-curvature-radius concave output mirror are used. The output spectra of this laser system with increased pump power are presented in Figs. 2(a)–2(f). The fundamental laser at 1064 nm oscillates first at an incident pump power of 0.03 W. The peak wavelength is located at 1064.4 nm with an FWHM of 0.03 nm. As shown in Fig. 2(a), when the incident pump power increases to 0.99 W, the Raman laser at 1176 nm with an FWHM of 0.02 nm appears, which corresponds to the first Stokes shift of 890 cm^{-1} for the fundamental laser at 1064 nm. The polarization states of lasers are examined by a Glan-Laser Calcite polarizer (Thorlabs). The results show that the polarization of Stokes laser is the same as that of its corresponding fundamental laser. The 1064-nm and 1176-nm lasers are measured to be linearly π-polarized. By further increasing the incident pump power to 4.8 W, the σ-polarized fundamental radiation at 1066.7 nm is detected. It should be noted that the polarization direction is orthogonal to the polarization direction of fundamental laser at 1064 nm. The frequency separation of the two wavelength lasers is about 0.71 THz. As the pump power reaches 6.3 W and 6.7 W, the σ-polarized Raman laser at 1168.4 nm and 1178.7 nm are observed, respectively, as shown in Fig. 2(b). Obviously, the Stokes wavelength at 1168.4 nm and 1178.7 nm come respectively from the first Stokes shift of 816 cm^{-1} and 890 cm^{-1} for the 1066.7-nm fundamental laser. According to the spontaneous Raman spectrum of *c*-cut Nd:YVO_4 crystal,[11,12,23] for σ-polarized pump, the Raman gain coefficients for three main Raman shifts at 890, 816, and 259 cm^{-1} are estimated at 4.5, 2.6, and 2.3 cm/GW, respectively. To our knowledge, the oscillation threshold of Raman laser is inversely proportional to Raman gain, thus the oscillation threshold of 1178.7 nm should be lower than that of 1168.4 nm, which is not in agreement with the experimental result. The explanation for this phenomenon may be that the π-polarized 1064-nm fundamental laser is preferentially converted into the Raman laser at 1176 nm by the 890-cm^{-1} Raman shift, which results in the decrease of the actual Raman gain of 890-cm^{-1} Raman shift for σ-polarized 1066.7-nm laser. Consequently, the Raman laser at 1168.4 nm oscillates first.

When the pump powers exceed 8 W and 9.9 W, two new σ-polarized fundamental wavelengths at 1062.8 nm and 1084 nm are detected as shown in Fig. 2(c). And when the pump power is increased to 11 W and 12.4 W, the corresponding first Stokes lines at 1174 nm and 1199.7 nm are found to reach their thresholds respectively as shown in Fig. 2(d). As pump power is further increased, the π-polarized fundamental line at 1085.6 nm and the corresponding 1st-stokes laser at 1201.6 nm began to oscillate at a pump power of 16.3 W and 17.3 W, respectively, as shown in Fig. 2(e). When the incident pump power is increased to 24.9 W, the last π-polarized fundamental line at 1073.6 nm appears. The output spectrum of the Raman laser under the maximum incident pump power of 26 W is shown in Fig. 2(f). It can be found that the linewidths (FWHM) of the 1064-nm fundamental laser and 1176-nm Stokes wavelength increase to 1.68 nm and 0.55 nm, respectively. Due to the noticeable spectral broadening of 1064-nm fundamental laser, the wavelength separation between the 1064 nm and 1062.8 nm becomes smaller, the gain competition between them turns more intense and suppresses the oscillation of 1062.8 nm, thus the fundamental laser at 1062.8 nm and its corresponding Raman laser at 1174 nm disappear. In addition, with the pump power increasing from 17.3 W to 26 W, the intensity of 1085.6-nm laser becomes stronger than that of 1084-nm laser (see Figs. 2(e)–2(f)). Because the intensity of 1084 nm decreases to a lower level than the Raman threshold, the corresponding 1199.7-nm Raman laser stops oscillating while 1084 nm (fundamental) still oscillates at the 26-W pump power. Finally, the fundamental laser oscillates separately at five wavelengths of 1064, 1066.7, 1073.6, 1084, and 1085.6 nm, while at the same time, the Raman laser oscillated at four wavelengths of 1168.4, 1176, 1178.7, and 1201.6 nm, respectively. The output wavelengths with their corresponding thresholds, Raman shifts and polarization states are given in Table 1. According to Refs. [5] and [6] for a four-level laser, the pump threshold of fundamental laser can be estimated by the formula

$$P_{\mathrm{th}} = \frac{\pi h \nu_{\mathrm{p}} (\omega_{\mathrm{p}}^2 + \omega_l^2)\,[-\ln(R) + L]}{4\eta_{\mathrm{p}}\sigma_{\mathrm{e}}\tau},$$

where σ_{e} is the emission cross-section. Therefore, the oscillation threshold of fundamental laser is proportional to the inverse of emission cross section at this wavelength. For the Nd:YVO_4 crystal, the emission cross sections are 13.4×10^{-19} cm^2 and 1.74×10^{-19} cm^2 at 1064 nm and 1085.5 nm for π-polarization and 2.95×10^{-19}, 2.26×10^{-19}, and 1.36×10^{-19} cm^2 at 1066.5, 1062.6, and 1083.3 nm for σ-polarization, respectively.[5,6] It can be observed that the order of oscillation of different fundamental lasers is consistent with the theoretical implications.

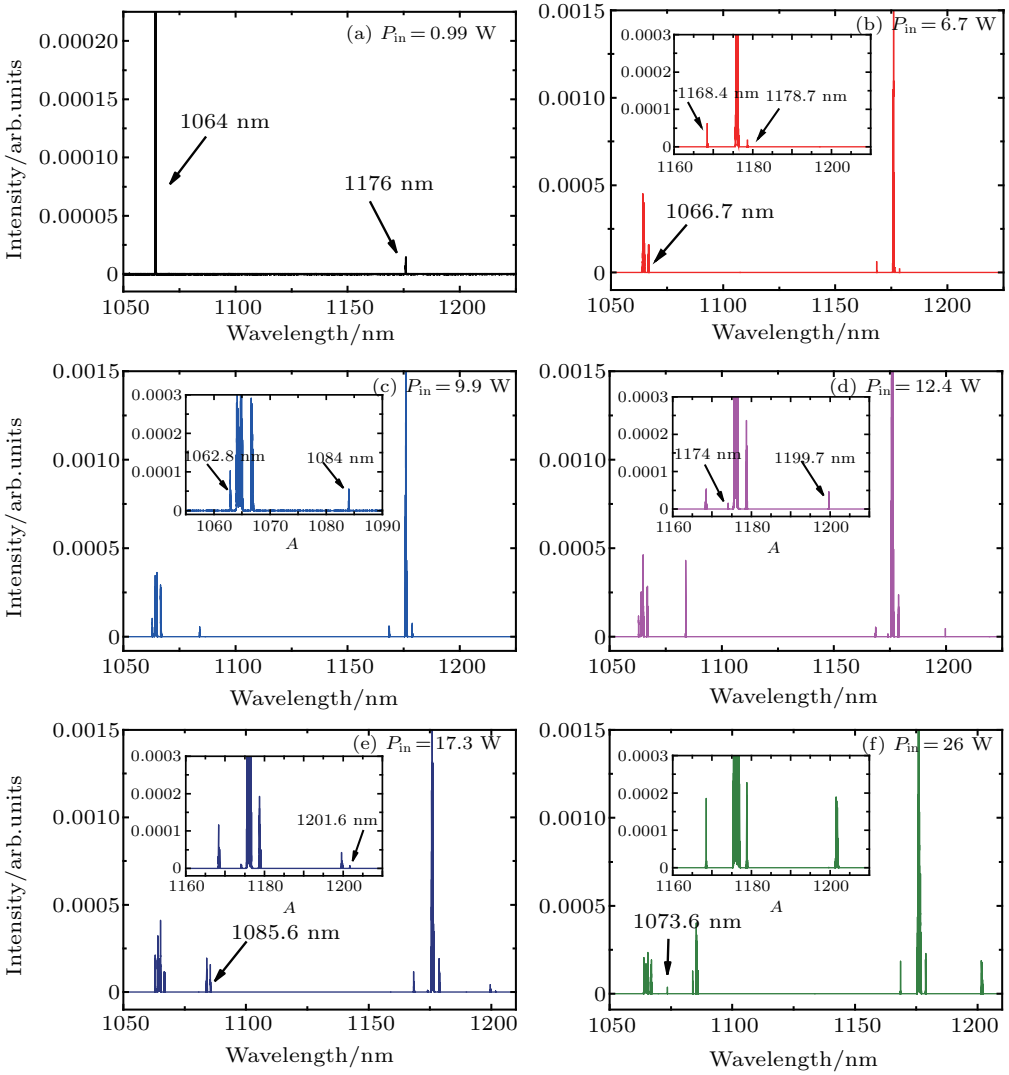


Fig. 2. Output spectra of CW self-Raman laser with 20-mm-long YVO_4/Nd:YVO_4/YVO_4 crystal under different incident pump powers: (a) $P_{in} = 0.99$ W, (b) $P_{in} = 6.7$ W, (c) $P_{in} = 9.9$ W, (d) $P_{in} = 12.4$ W, (e) $P_{in} = 17.3$ W, and (f) $P_{in} = 26$ W.

Table 1. Summary of Raman laser output wavelengths with their corresponding thresholds, Raman shifts, and polarization states for 20-mm-long crystal.

Fundamental wavelength/nm	Threshold/W	Raman shift/cm^{-1}	1st-Stokes wavelength/nm	Threshold/W	Polarization state
1064	0.03	890	1176	0.99	π
1066.7	4.8	816	1168.4	6.3	σ
		890	1178.7	6.7	σ
1062.8	8.0	890	1174	11.0	σ
1084	9.9	890	1199.7	12.4	σ
1085.6	16.3	890	1201.6	17.3	π
1073.6	24.9				π

For comparison, we also investigate the performances of the CW self-Raman lasers when two other crystals are used. Since more efficient Raman conversion can be obtained by increasing the length of self-Raman crystal, output spectra are different when using crystals with different lengths. For example, when the 10-mm-long Nd:YVO_4 crystal is used, only the fundamental laser line at 1064 nm and first-Stokes line at 1176 nm are observed in the experiment. When the 14-mm-long composite YVO_4/Nd:YVO_4/YVO_4 crystal is used, multi-wavelength laser outputs are also realized. With pump power increases from 6.01 W to 22 W, the fundamental laser oscillates separately at 1062.8, 1064, 1066.7, 1084, and 1085.6 nm, while the Raman laser oscillates separately at 1168.4, 1176, 1178.7, 1199.7, and 1201.6 nm. However, when pump power is increased to the maximum incident pump power of 26 W, only 1064-, 1085.6-, 1176-, and 1201.6-nm lasers still oscil-

late. Therefore, the number of the oscillating wavelengths is less than that of self-Raman laser with the 20-mm-long composite Nd:YVO_4, and the threshold of each wavelength is also slightly higher. In addition, under the maximum pump power of 26 W, the residual non-polarized 879-nm pump power (leaking through the output mirror) is measured to be 2.183, 4.5, and 4.71 W for 20-mm, 14-mm, and 10-mm-long crystal, corresponding to an absorption fraction of 91.6%, 82.7%, 81.9%, respectively. However, as reported in Ref. [25], a 0.3-at.%, 20-mm-long YVO_4/Nd:YVO_4/YVO_4 crystal can absorb only $\sim 78\%$ of the common 880-nm non-polarized incident pump power. This reveals that better absorption is achieved by using the narrow-linewidth wavelength-locked LD. These experimental results show that it is easier to achieve multi-wavelength laser output by increasing the length of self-Raman crystal. This is because longer self-Raman crystal leads to higher absorption efficiency of pump laser, higher Raman conversion efficiency, and lower threshold of laser oscillation. Besides, it is worth mentioning that when the Raman output mirror is replaced by a flat output mirror with 10% transmission at 1064 nm, only the 1064-nm fundamental laser is detected. This shows that in the Raman laser, Raman conversion acts as a loss for the 1064-nm fundamental laser, thus resulting in the oscillation of other lower-gain fundamental laser.

Moreover, it should be noted that when the 14-mm-long composite Nd:YVO_4 crystal is pumped by the traditional 808-nm LD, we find only the emission lines at 1064 nm and 1176 nm as reported in our previous work.[27] And when 20-mm-long composite Nd:YVO_4 crystal is pumped by the 808-nm LD, Only two fundamental lines at 1064 nm and 1066 nm and three Stokes lines at 1168, 1176, and 1178 nm are observed. This indicates that a second reason for the multi-wavelength oscillation in the CW Nd:YVO_4 self-Raman laser may be lower thermal loading provided by the employment of 879-nm LD, which can be understood by the fact that an increase in crystal temperature will cause both the emission cross section of fundamental laser[28] and the Raman gain to decrease. Based on these observations, the multi-wavelength laser oscillation of the CW Nd:YVO_4 self-Raman laser should be the result of higher pump absorption, higher fundamental and Raman laser gain, and lower thermal effect, which are achieved by the use of wavelength-locked 879-nm LD and longer crystal. Therefore, the other weak fundamental and Stokes lines can reach the oscillating thresholds and multi-wavelength laser output is realized.

When the 20-mm-long crystal is used, not only is the output spectrum richest but also the output power of Raman laser is highest. Due to the small wavelength separation, it is too difficult to measure the output powers of different fundamental and Raman lasers individually. Figure 3(a) shows the total Raman output power versus the incident pump power for several output couplers with different radii of curvature (50, 100, 200, 300, and 500 mm) when 20-mm-long crystal is used. The highest Raman output power is obtained when a 100-mm concave output mirror is used. The reasons are as follows. First, the Raman conversion efficiency is proportional to the power density of fundamental laser. An ABCD matrix analysis of the resonator shows that the TEM_{00} fundamental mode size decreases with the curvature radius of the output mirror decreasing. Therefore, the smaller the radius of curvature of output mirror, the smaller the cavity mode size is; the greater the power density of the fundamental laser in the Raman crystal, the higher the Raman output power is. As such, higher conversion efficiency will ultimately be achieved. Second, although the curvature radius of 50-mm output mirror is the smallest, it is difficult to clean the mirror because of its strongly curved surface, and the alignment of resonant cavity is difficult, resulting in a lower output power. Figure 3(b) shows the total output power of the fundamental and Raman lasers with respect to the incident pump power when the 20-mm-long crystal and 100-mm concave output mirror are used. Under the maximum incident pump power of 26 W, a total output power of 2.56 W of Raman laser is measured through the output

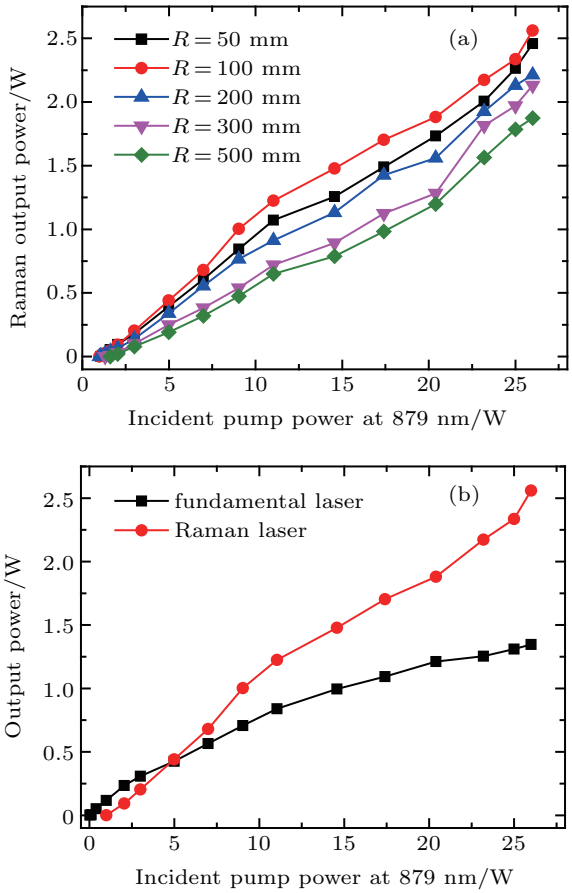


Fig. 3. (a) Plots of Raman output power versus incident pump power for several output couplers with different radii of curvature (50, 100, 200, 300, and 500 mm), and (b) plots of output power at fundamental and Raman laser versus incident pump power at 879 nm.

coupler. The Raman threshold is only 0.99 W, corresponding to a diode-to-Stokes conversion efficiency of 9.8% and a slope efficiency of 10.2%. It should be noted that the residual fundamental (1064, 1066.7, 1062.8, and 1073.6 nm) output power was 1.35 W, measured behind the output mirror and a filter (FLH1064-8) at the pump power of 26 W. This indicates that the reflectivity of cavity mirror at 1064-nm fundamental laser is not high enough and the fundamental laser is not effectively converted to Raman laser either. Since neither the saturation of the output power nor the optical damage is observed under the maximum pump power, the Raman output power can be expected to increase obviously through increasing the pump power and optimizing the coating parameters of the cavity mirrors.

4. Conclusions

In this research, we demonstrate a multi-wavelength CW self-Raman laser with a composite YVO_4/Nd:YVO_4/YVO_4 crystal pumped by a wavelength-locked LD at 879 nm to minimize the thermal loading and maximize the Raman gain and pump absorption. To the best of our knowledge, the fundamental lasers at 1064, 1066.7, 1073.6, 1084, and 1085.6 nm, and the first Stokes lasers at 1168.4, 1176, 1178.7, and 1201.6 nm oscillate simultaneously in an *a*-cut Nd:YVO_4 crystal for the first time. When a 20-mm-long composite crystal is used, the maximum total Stokes output power is measured to be 2.56 W under an incident pump power of 26 W, corresponding to an optical conversion efficiency of 9.8%. With further optimization of the mirror coating, higher output power and conversion efficiency can be anticipated. The polarizations of some closely spaced wavelengths are orthogonal. Such a simultaneous orthogonally polarized multi-wavelength laser source provides the more flexible selection of laser wavelengths, and it can be used to generate more-closely spaced CW visible lines and terahertz radiation by combining with second harmonic generation and difference frequency generation.

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