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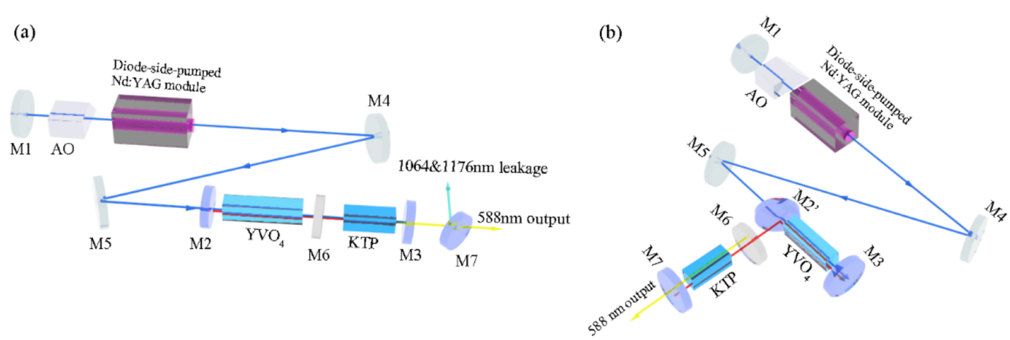


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# 13.7-W 588-nm Yellow Laser Generation by Frequency Doubling of 885-nm Side-Pumped Nd: YAG-$YVO_4$ Intracavity Raman Laser

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**Abstract:** An actively Q-switched all-solid-state $YVO_4$ Raman laser, which used a 885-nm side-pumped Nd:YAG laser as the fundamental wavelength and delivered yellow output, is demonstrated. An in-band pump scheme is adopted to mitigate the thermal effects in the laser crystal and a Z-shaped laser cavity is used to compensate thermal lensing further. By intracavity frequency doubling of the Stokes wave with KTP crystal, 13.7-W yellow output at a wavelength of 588 nm, with a pulse repletion frequency of 10 kHz, was obtained under a diode pump power of 233 W. Additionally, single-pulse energy was 1.37 mJ with the pulse-width of 12.5 ns, corresponding to a peak power of 110 kW.

**Index Terms:** 885-nm side-pumped, Raman laser, coupled stokes cavity, yellow light.

## 1. Introduction

Yellow-orange lasers in the spectral range of 560–600 nm have been used in various applications, including laser guide star systems, laser therapy, and laser Doppler velocimetry [1]–[3]. Most laser frequencies in this region can be generated by several approaches, such as laser diode (LD)-pumped $Pr^{3+}$/$Tb^{3+}$-doped lasers [4], sum-frequency mixing of two $Nd^{3+}$-doped laser lines [5]–[7], optical parametric oscillators [8]–[10], dye lasers [11], and fiber or all-solid-state Raman lasers [12]–[23].Compared with other techniques, the beam cleanup effect of stimulated Raman scattering (SRS) helps Raman lasers realize good beam quality and hole-burning-free SRS gain can narrow the spectral linewidth [24]–[26]. A Stokes pulse also exhibits a significantly narrower pulse duration than those of their fundamental wavelength [27]. These properties make Raman lasers a promising method for high-performance yellow output. Currently, Raman fiber lasers can achieve an output

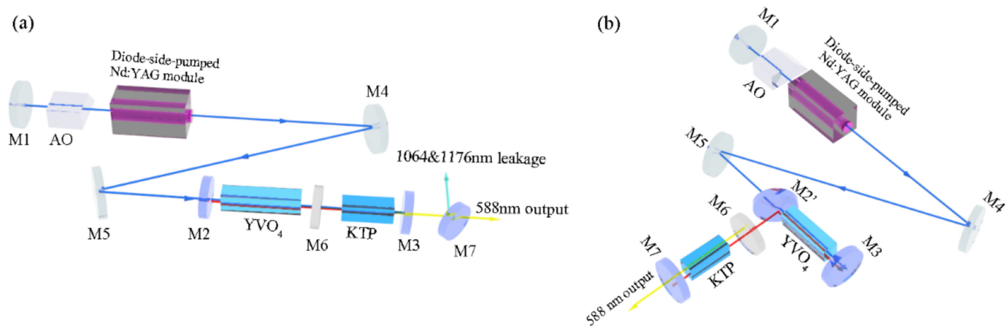


Fig. 1. Schematic of the 588 nm yellow lasers based on an internal-cavity frequency doubling of in-band 885-nm side-pumped Nd:YAG/$YVO_4$ Raman laser with (a) linear Stokes cavity and (b) L-shaped Stokes cavity.

power of tens to hundreds of watts in the yellow-orange regions [21]–[23]. However, limited by the intrinsic physical characteristics of the fibers, it is difficult to obtain yellow coherent light with large single-pulse energy through the approach of Raman fiber lasers. Therefore, compared with other methods, all-solid-state Raman lasers are the appropriate method to obtain yellow coherent light with good beam quality, large single-pulse energy, narrow linewidth etc.

Both end-pumped and side-pumped all-solid-state lasers have been used as the fundamental wavelength of Raman lasers. End-pumped yellow Raman lasers exhibit good conversion efficiency and beam quality, but the output power is limited by the maximum pump intensity that allowed by the crystal. The reported highest power of the yellow end-pumped Raman laser is 7.9-W at 588-nm based on an acousto-optic Q-switched Nd:$YVO_4$ self-Raman laser, demonstrated by Zhu et al. in 2009 [14]. However, the reported good performance relied on utilization of high-quality crystals, which can be expensive and inaccessible. Actually, the problem of low average output power of end-pumped yellow Raman lasers has not been effectively solved. Compared with the end-pumped scheme, side-pumped yellow Raman lasers are usually much more powerful due to a higher pump power. In 2010, Cong et al. demonstrated an intracavity Raman laser wherein a side-pumped Nd:YAG laser served as the fundamental wavelength [16]. By intracavity Raman conversion and second harmonic generation, a yellow beam with the power of 8.3 W was obtained at a pulse repletion frequency (PRF) of 15 kHz, which corresponded to a single-pulse energy of 0.55 mJ.

The power performance of solid-state lasers is usually limited by thermal effects. Reasonable thermal management can significantly improve the laser output power. For Raman lasers, it has also been proven that thermal management via in-band pumping results in enhanced performance [13]. In this paper, effective thermal management of a frequency-doubled intracavity Raman laser is achieved by in-band pumping of the side-pumped Nd:YAG fundamental wavelength using an 885-nm laser diode and compensating the thermal lens with a Z-shaped cavity design. A L-shaped coupled Stokes cavity is also optimized to avoid element damage and improve the conversion efficiency of Stokes light. By intracavity SRS conversion using an $YVO_4$ crystal and intracavity frequency doubling of the Stokes wave with a potassium titanyl phosphate (KTP) crystal, 13.7-W pump-limited yellow (588 nm) output was obtained under a 233-W pump power at a PRF of 10 kHz. The single-pulse energy was 1.37 mJ with the pulse width of 12.5 ns, corresponding to a peak power of 110 kW.

## 2. Experimental Setup

The 588 nm yellow lasers based on an internal-cavity frequency doubling of in-band 885-nm side-pumped Nd:YAG/YVO4 Raman laser with linear and L-shaped Stokes cavity are shown in Figs. 1(a) and (b), respectively. A customized side-pumped Nd:YAG module was employed for providing the fundamental laser. The Nd:YAG crystal, 0.6 at.%, $\Phi$4 mm $\times$ 120 mm in size, was coated for anti-reflectivity (AR) at 1064 nm. A common Z-shaped cavity (designated by mirror path M1-M4-M5-M3 for both two cavities in Fig. 1) was adopted for the fundamental wavelength for the purpose of compensating thermal lensing in the laser crystal. Mirror M1 and M3 are flat mirrors while M4 and M5 are flat-concave mirrors with radii of curvature of 300 mm and 200 mm, respectively. The concave mirrors of M4 and M5 can enlarge the stable region of the fundamental field and improve the tolerance of the variations of thermal lensing of the laser and Raman crystal by elaborate design. All four mirrors, which made up the 1064-nm fundamental wavelength cavity, were coated for high-reflectivity (HR) at 1064 nm. The folding angle was set to 10° to minimize the influence of astigmatism. An acousto-optic Q-switch with an ultrasonic frequency of 27 MHz was used to operate the laser in a pulsed scheme.

During the experiment, the power performance of the yellow output was investigated with both a linear Stokes cavity and an L-shaped Stokes cavity. For the linear Stokes cavity, a flat mirror (M2) coated for AR at 1064 nm and HR at 1176 nm, was used to compose the Stokes cavity with M3. The mirror M3, which serves as the yellow output coupler, had an HR coating for 1176 nm and an AR coating for 588 nm. For the L-shaped cavity, a flat mirror (M2'), coated for AR at 1064 nm and HR at 1176 nm with a 45° angle of incidence, was used to fold the Stokes light. Another flat mirror M7, identical to M3, composed the Stokes cavity with M2' and M3. An a-cut $YVO_4$ crystal with the dimensions of 4 $\times$ 4 $\times$ 30 mm$^3$ was used as the Raman crystal. A 15-mm-long KTP crystal (cut at $\theta = 68.7°$ and $\varphi = 0°$), placed between the $YVO_4$ crystal and M3 in the linear Stokes cavity or M2' and M7 in the L-shaped Stokes cavity, was used to frequency double the intracavity Stokes field. Both crystals had an AR coating for 1064 and 1176 nm, while the KTP crystal was also coated for AR at 588 nm. The two crystals were both wrapped in indium foil and placed in a water-cooled copper holder at 18°C. A flat dichroic mirror (M6), coated for HR at 588 nm and AR at 1064 nm and 1176 nm, was placed between the $YVO_4$ crystal and the KTP crystal to collect the backward-propagating yellow harmonic. The total fundamental laser cavity length was 785 mm. The distances between each element were: M1 to Nd:YAG = 100 mm; Nd:YAG to M4 = 150 mm; M4 to M5 = 250 mm; M5 to $YVO_4$ = 100 mm; M2 to M3 = 90 mm; $YVO_4$ to KTP = 40 mm (linear Stokes cavity); and M3 to M2' to M7 = 90 mm. (L-shaped Stokes cavity).

## 3. Results and Discussion

The laser performance was first investigated while using the Z-shaped fundamental cavity and then the linear Stokes cavity. Using an ABCD matrix, and considering the thermal lens ($\sim$835 mm) induced by the $\sim$190 W diode pump power in the Nd:YAG laser module [20], the fundamental and Stokes beam radii in the $YVO_4$ Raman crystal are calculated as 235 and 217 $\mu$m, respectively. The radius of Stokes beam in the KTP crystal is 168 $\mu$m. The power transfer of the Raman laser is plotted in Fig. 2 (black squares). The yellow output (SRS) threshold is 82 W and a maximum average output power of 10.1 W is obtained under a launched pump power of 190 W, with a corresponding optical efficiency of 5.3%. The yellow output power increases linearly with pump power, without evidence of saturation. However, further increasing the pump power results in damage of dichroic mirror M6, which can be attributed to the high circulating fundamental and Stokes power in the cavity.

To avoid damaging mirror M6, the L-shaped Stokes cavity arrangement was adopted to move M6 out of the fundamental cavity. The total fundamental and Stokes cavity lengths are kept unchanged. The radii of the fundamental and Stokes beams in the $YVO_4$ crystal are 240 and 210 $\mu$m, respectively. This considers an $\sim$753 mm thermal focal length in the Nd:YAG crystal under a 233-W incident diode pump (885 nm) [20]. The radius of Stokes beam in the KTP crystal is 170 $\mu$m. The average yellow output power at PRFs of 10 kHz (red circles) and 20 kHz (blue triangles) are plotted in Fig. 2. The SRS threshold under PRFs of 10 kHz and 20 kHz are 91 W and 99 W, respectively, as well as their output powers without saturation are 13.7 W and 9.45 W under the maximum pump power of 233 W, respectively. Coating damage of mirror M6 did not occur with this cavity arrangement. It should be also mentioned that the output power of yellow laser

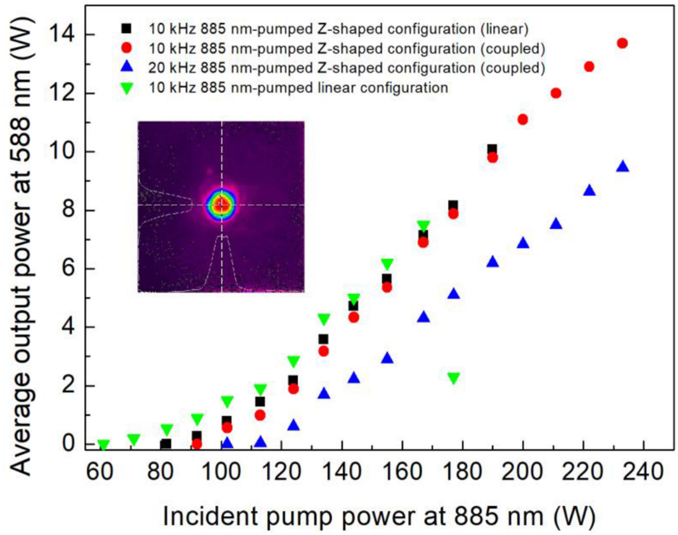


Fig. 2. The power transfer of the 588 nm yellow light, with different cavity arrangements. Inset: the beam profile of yellow output at the maximum power of 13.7 W.

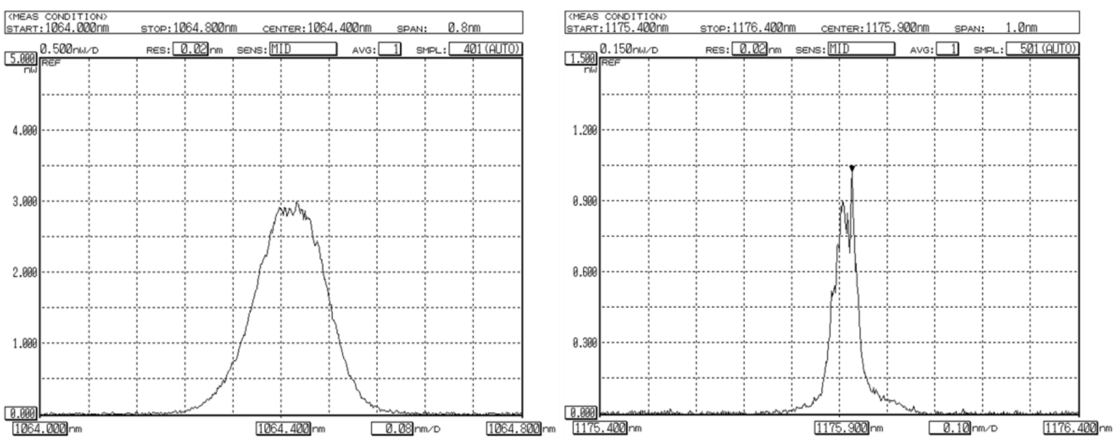


Fig. 3. Fine spectrum at (a) 1064 nm and (b) 1176 nm recorded at the maximum LD pump power.

can be further improved by replacing the customized 885-nm side-pumped Nd:YAG module with a mature commercial one, which exhibits higher electro-optic efficiency, better thermal performance and power stability. At the maximum output power of 13.7 W, the M2 factors of the yellow output in the x and y directions are measured to be 7.7 and 7.9 by the knife-edge scanning. The beam profile was recorded by a camera (Ophir Pyrocam III), which is shown in the inset of Fig. 2.

For comparison, the yellow Raman laser with a linear cavity was investigated, which was similar to the regime that described in our previous work [20]. The results are plotted in Fig. 2 (green triangles). With a PRF of 10 kHz, the yellow output power rolls over after the pump power exceeds 177 W due to the thermal lens effect. The results reveal that the Z-shaped fundamental cavity enlarges the cavity stable zone against the thermal focal length and provides a much higher maximum output power than that of the linear fundamental cavity.

The spectral range of our optical spectrum analyzer (OSA Yokogawa AQ6370D) does not cover the 588 nm yellow output. Fig. 3 shows the fine spectrum of fundamental and Stokes wave recorded by OSA, with a resolution of 0.02 nm at the maximum LD pump power of 233 W. The central wavelength of the Stokes wave is 1175.92 nm and the spectral linewidth is $\sim$0.05 nm, which is

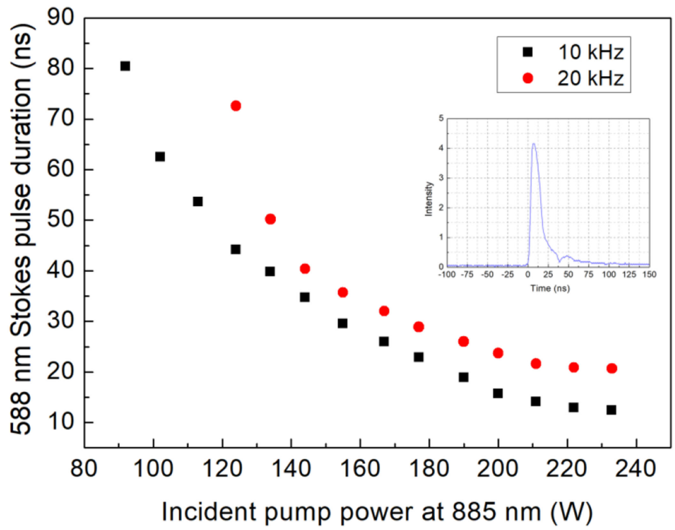


Fig. 4. The pulse duration of yellow output as a function of diode pump power. Inset: temporal pulse shape of oscilloscope trace at the maximum Stokes output power of 13.7 W.

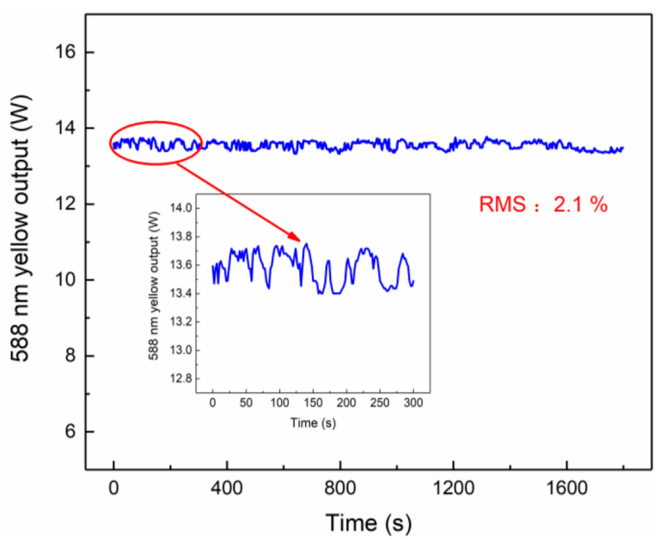


Fig. 5. The power stability of the 588 nm yellow output at the maximum power over 30 min with the L-shape Stokes cavity. Inset: The short-term power stability over the first 5 min.

smaller than that of the fundamental wave (~0.13 nm). This is because the gain of the SRS process comes from the fundamental field rather than the stored energy in the gain medium, which makes SRS process not suffer from spatial hole burning [26]. The linewidth of the yellow output should be a little smaller than this value. Using a fast photodiode (Thorlabs DET08C) and an oscilloscope (Tektronix DPO2024B), we recorded the pulse duration of the 588-nm yellow laser, as shown in Fig. 4. The pulse duration of the yellow light is 12.5 ns and 20.8 ns under a pump power of 233 W at PRFs of 10 kHz and 20 kHz, respectively. The inset of Fig. 4 shows the oscilloscope trace with a 233-W pump and 10-kHz PRF. It should be noted that the pulse duration of stokes field is related to the lifetime of the Stokes photons, the pulse energy and the pulse duration of the fundamental field, and the parameters of the Raman medium [27]. The pulse duration of Stokes field is mainly affected by the performance of the fundamental frequency field when other parameters remain constant, so the pulse duration of yellow laser at 10 kHz is smaller than that of 20 kHz.

The power stabilities of the linear and L-shape Stokes cavity were both measured. However, the yellow output power of linear Stokes cavity decreased significantly after 5 min, owing to the damage of dichroic mirror M6. Fig. 5 shows the power stability of the yellow output measured over 30 min with the L-shape Stokes cavity, which exhibited a root-mean-square (RMS) fluctuation of 2.1%. The inset of Fig. 5 shows a short-term power stability over the first 5 min.

## 4. Conclusion

In this work, we demonstrated a high-power frequency-doubled intracavity $YVO_4$ Raman laser with a side-pumped Nd:YAG laser as the fundamental wavelength. An 885-nm in-band pump scheme is adopted to mitigate the thermal effects and a Z-shaped laser cavity is used to compensate thermal lensing further. A L-shaped coupled Stokes cavity is also optimized to avoid element damage and improve the conversion efficiency of Stokes light. A 13.7-W output power at 588 nm is obtained by frequency-doubling of the Stokes light under a 233-W diode pump with a PRF of 10 kHz. The pulse energy of the yellow output reaches 1.37 mJ and the peak power is $\sim$110 kW. To the best of our knowledge, this is the maximum output power reported for all-solid-state Raman yellow lasers wherein the results are only limited by the pump. It should be also mentioned that the output power of yellow laser can be further improved by replacing the customized 885-nm side-pumped Nd:YAG module with a mature commercial one, which exhibits higher electro-optic efficiency, better thermal performance and power stability.

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