Generation of Higher Order Vortex Beams From a YVO$_4$/Nd:YVO$_4$ Self-Raman Laser via Off-Axis Pumping With Mode Converter

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Abstract—The generation of high-order Hermite-Gaussian (HG) beams at the Stokes wavelength in a YVO$_4$/Nd:YVO$_4$ self-Raman laser with off-axis pumping is demonstrated. The high-order vortex beams at the Stokes field are successfully created by transforming these HG modes via an extra-cavity mode converter. The stimulated Raman scattering (SRS) threshold pump power for the diode-end-pumped laser is theoretically analyzed to verify the feasibility of generating high-order HG modes by off-axis pumping. At a pump power of 18.6 W, the SRS output powers can be higher than 1.0 W for the HG modes from TEM$_{0,0}$ to TEM$_{3,0}$. Under the same pump power, the maximum order can be up to TEM$_{28,0}$.

Index Terms—Optical vortices, Raman scattering, diode pumping, Beam transformation.

I. INTRODUCTION

THE optical vortex beam is a helical-phased light beam that possesses orbital angular momentum due to the phase singularity. Based on this distinct feature, optical vortex beams have been generally used in the study of quantum entanglement [1], optical tweezers [2]–[4], optical testing [5], and trapping and guiding of cold atoms [6]–[8]. An optical vortex beam can be generated directly by utilizing intra-cavity spiral phase plates [9], pumping with an annular shaped beam [10], [11], or utilizing a resonator mirror with a defect spot [12], [13] to force the laser to oscillate on a Laguerre-Gaussian (LG) mode rather than a Hermite-Gaussian (HG) mode. On the other hand, several extra-cavity devices such as astigmatic lenses [14], [15], spiral phase plates [16], computer-generated holographic converters [17], and optical wedges [18] have also been employed to convert high-order HG modes into optical vortex beams. By means of the second-harmonic generation which is associated with the second order $\chi^{(2)}$ nonlinearity, frequency doubled optical vortex beams have been further achieved [14], [19].

Stimulated Raman scattering (SRS) is a practical and widely accepted method to operate laser sources in new wavelengths

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Digital Object Identifier 10.1109/JSTQE.2014.2324754

based on a third-order nonlinear optical process. In the earlier Raman lasers, the Q-switched approaches with high-peak power were extensively employed to reach the high SRS threshold [20]–[23]. In 2005, the first continuous-wave (CW) Raman laser was successfully achieved by using a high-Q Fabry-Perot cavity to reduce the SRS threshold [24]. Since then, several CW self-Raman lasers had been exploited because of their promising applications in optical communications and biomedicine [25]–[29]. Recently, Lee *et al.* have successfully obtained an optical vortex beam at the first Stokes wavelength from a CW Nd:GdVO$_4$ self-Raman laser directly by producing defect spots on the output coupler (OC) [30]. Although intracavity self-Raman optical vortex beams have been demonstrated, it will be more useful to develop an approach for generating various different higher-order vortex beams at the Stokes field for the study of super-resolution microscopic techniques [31] or nanomaterial processing [32], [33].

High-order HG modes can be generated easily by displacing the pump beam from the optical axis of the laser resonator [34]; however, a large off-axis displacement also results in a higher threshold power which will hinder the generation of high-order HG beams at the Stokes wavelength. Therefore, it is of great importance to explore the feasibility of generating high-order HG modes at the Stokes field for transforming these beams into high-order vortex beams with mode converter. In this work, we report the realization of generating high-order HG modes at the Stokes field from a YVO$_4$/Nd:YVO$_4$ self-Raman laser with an off-axis pumping scheme. To begin with, we employ a partial-reflection (PR) coated concave mirror as OC to investigate the performance for the generation of high-order HG beams at the fundamental wavelength. At an incident pump power of 2.5 W, the output efficiency for the generation of high-order HG modes can be maintained nearly the same for the order up to TEM$_{24,0}$. The measured output powers for the TEM$_{34,0}$ is still up to 1.0 W under the same pump power. For operating the wavelength of the laser output at the first Stokes wavelength of 1176 nm, the PR coated OC is replaced by a dual high-reflection (HR) coated concave mirror. The SRS threshold pump powers are theoretically analyzed to verify the feasibility of generating high-order HG modes at the Stokes field by off-axis pumping. The experimental results of the SRS threshold powers for high-order HG beams correspond to the theoretical predictions. We find the SRS output powers for the HG TEM$_{n,0}$ modes decrease slowly only in the lower-order regime and decay rapidly as the order is higher than TEM$_{3,0}$ mode. At an incident pump power of 18.6 W, the SRS output powers for the TEM$_{n,0}$ modes with
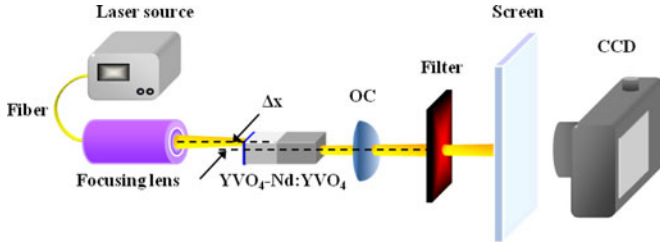
Fig. 1. Experimental setup for a high-order HG $TEM_{n,0}$ YVO_4/Nd:YVO_4 laser in a simple plano-concave resonator with an off-axis pumping scheme.

Fig. 2. The average output power of the fundamental wave versus the off-axis displacement Δx at a pump power of 2.5 W.

$n = 0 - 3$ are measured to be higher than 1 W. Although the SRS output powers decrease rapidly as the order is higher than $TEM_{3,0}$ mode, the order of the HG modes can still reach up to $TEM_{28,0}$ at the same pump power. Finally, high-order vortex beams at the first Stokes wavelength of 1176 nm are successfully achieved by converting these high-order HG beams through a $\pi/2$ cylindrical-lens mode converter.

II. EXPERIMENTAL SETUP

The schematic diagram of the experimental setup is depicted in Fig. 1. The gain medium was a 8-mm long, *a*-cut 0.5 at.% Nd:YVO_4 crystal combined with a 2.5-mm long undoped YVO_4 crystal at the pumped facet to reduce the thermal effect. The front facet of the composite crystal was coated to form the input flat mirror with HR coating at the fundamental wavelength of 1064 nm ($R > 99.9\%$) and the first Stokes wavelength of 1176 nm ($R > 99.9\%$), and high-transmission coating at the pump wavelength of 808 nm ($T > 95\%$). The other facet was anti-reflection coated at 1064 and 1176 nm ($R < 0.2\%$). Furthermore, the active medium was wrapped with indium foil and mounted in a water-cooled copper block with the water temperature maintained at around 12 °C. Two 100-mm radius-of-curvature concave mirrors with different coating were used to be the OC. One was PR coated at 1064 nm ($R = 95\%$) for investigating the generation of HG modes at fundamental wavelength, the other was dual-HR coated at 1064 nm ($R > 99.8\%$) and 1176 nm ($R > 99.3\%$) for operating the laser output at the first Stokes wavelength of 1176 nm. To obtain a small spot radius of the laser beam, the laser resonator was set to be as compact as possible with a cavity length of 12 mm, corresponding to a cavity mode radius of 105 μm. The pump source was a 20-W fiber-coupled 808-nm laser diode with a core diameter of 200 μm and a numerical aperture of 0.22. A focusing lens set with 25-mm focal length and 92% coupling efficiency was used to reimage the pump beam into the laser crystal with a pump spot size of 120 μm. Experimental patterns of high-order HG and LG modes were recorded by a CCD camera.

III. EXPERIMENTAL RESULTS AND DISCUSSION

In the beginning, we utilized the PR coated OC to exploring the generation of high-order HG modes at the fundamental wave. As displacing the pump beam from the optical axis, the high-order HG beams were generated in the step-wise manner. Fig. 2 shows the average output power of the fundamental wave versus
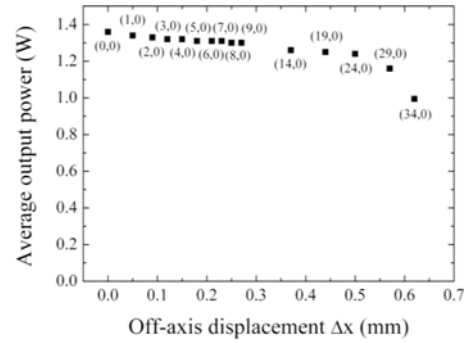
the off-axis displacement Δx at an incident pump power of 2.5 W. When the off-axis displacement Δx was greater than 0.62 mm, the output power was found to decrease considerably due to the cavity-size induced diffraction losses. We can see that the average output powers varied slightly in the range of 1.36–1.24 W for the $TEM_{n,0}$ modes from $n = 0$ to $n = 24$ at an incident pump power of 2.5 W, and it decreased almost linearly with the slope of -0.23 W/mm. On the other hand, the output powers decayed remarkably when the order was higher than $TEM_{24,0}$ mode. However, the measured output powers for $TEM_{29,0}$ and $TEM_{34,0}$ mode were still as high as 1.16 and 1 W, respectively. This result indicates that the laser system has high stability and is insensitive to the cavity losses. Based on the good performance as displayed in the fundamental field, we expected that the tolerance of the off-axis displacement for the Stokes field will still be good enough to maintain high SRS output power up to higher-order HG mode.

To create high-order HG modes at the first Stokes wavelength of 1176 nm, the PR coated OC was replaced by the intermediately HR coated OC. The diode pump power required to reach the high SRS threshold can be described in a simplified expression given by [35]

$$P_{\text{th,Raman}} = \frac{A_R}{g_R l_R} \frac{\lambda_F}{\lambda_p} \frac{(T_s + L_s)(T_F + L_F)}{2} \quad (1)$$

where A_R is the spot area of the Stokes field, g_R is the stimulated Raman gain coefficient, l_R is the length of the Raman crystal, λ_F and λ_P is the wavelength of the fundamental and pump radiation, respectively. T_S, L_S and T_F, L_F are the output coupling transmissions and round-trip losses for the Stokes and fundamental fields, correspondingly. Considering the oscillation in the laser resonator with an off-axis pumping scheme is a high-order HG $TEM_{n,0}$ mode, the overlapping of the pump and lasing area should be of concern and the spot area A_R must be modified as shown in (2) [34], shown at the bottom of the next page, where $\delta = \Delta x/\omega_l$ is the dimensionless off-axis displacement, $a = \omega_p/\omega_l$ is the pump-to-mode size ratio, ω_p and ω_l is the spot radius of the pump and laser beam, respectively, and $H_n()$ is the Hermite polynomial of order n. Substituting Eq. (2) into (1), the SRS threshold pump power for the single $TEM_{n,0}$ mode $P_{\text{th,Raman}}(\delta;a)$ can be estimated in terms of
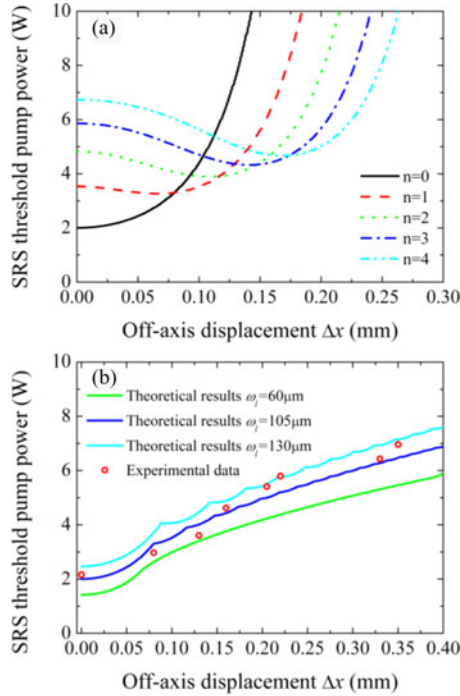
Fig. 3. (a) The dependence of the SRS threshold pump power on the off-axis displacement for the first five $\text{TEM}_{n,0}$ modes; (b) The experimental and theoretical results of the SRS threshold pump power versus the off-axis displacement Δx for a range of cavity mode radii.

Fig. 4. The average output power of the Stokes wave versus the off-axis displacement Δx for an cavity mode radius of 105 μm at a pump power of 18.6 W.

dimensionless off-axis displacement δ and pump-to-mode size ratio a. The theoretical results of the SRS threshold pump power with respect to the off-axis displacement Δx for the HG $\text{TEM}_{n,0}$ modes with $n = 0 - 4$ is depicted in Fig. 3(a). The parameters for the calculation are shown as follows: $g_R = 4.5$ cm/GW, $l_R = 10.5$ mm, $\lambda_F = 1064$ nm, $\lambda_P = 808$ nm, $\omega_p = 120$ μm, $\omega_l = 105$ μm, $T_s = 0.7\%$, $L_s = 0.2\%$, $T_F = 0.2\%$, $L_F = 0.2\%$, which are determined by the experimental conditions. The result indicates that the SRS threshold pump power fluctuates with the off-axis displacement because of the property of Hermite polynomials. The transverse mode with the minimum SRS threshold pump power will dominate the oscillation firstly for a given Δx. Consequently, it is helpful to define the minimum SRS threshold pump power for the oscillation as a function of pump-to-mode size ratio and dimensionless off-axis displacement, which can be expressed as

$$P_{\text{th,Raman,min}}(\delta; a) = \min\{P_{\text{th,Raman}}(\delta; a)\} \quad (3)$$

We calculate Eq. (3) with the same parameters and the result is shown in Fig. 3(b). It can be seen that the smaller the cavity mode size is, the lower the SRS threshold pump power is. The experimental data of the SRS threshold pump power versus the
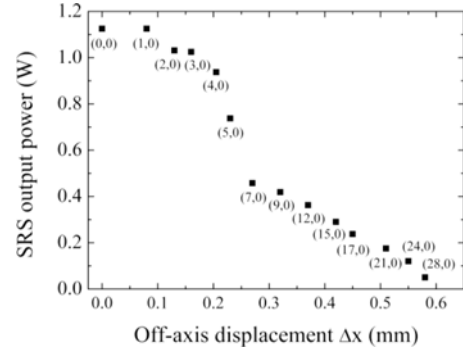
off-axis displacement is also plotted by the red points in this figure. Because the SRS conversion efficiency depends on the dopant concentration, the SRS threshold powers for the $\text{TEM}_{0,0}$ mode at different pump positions are also different. Therefore, the experimental results are quite consistent with the theoretical predictions with small variation on the pump size.

Fig. 4 shows the experimental results of the SRS output power with respect to the off-axis displacement at an incident pump power of 18.6 W. Since the intracavity SRS efficiency is significantly sensitive to the cavity losses, the SRS output powers for the HG $\text{TEM}_{n,0}$ modes varied slightly only in the low-order regime. The measured SRS output powers for the first four $\text{TEM}_{n,0}$ modes were all higher than 1 W at an incident pump power of 18.6 W. As the order of the HG modes was higher than $\text{TEM}_{3,0}$ mode, the SRS output powers were found to decrease rapidly caused by some additional cavity losses such as thermal loading or purity in the gain medium. However, the maximum order of the HG modes was recorded to reach up to $\text{TEM}_{28,0}$ under the same pump power. For investigating the influence of the spot radius of the laser beam on the maximum order of the HG modes, we increased the cavity length to 48 mm which corresponds to a cavity mode size of 130 μm. The dependence of SRS threshold pump powers on the off-axis displacement is illustrated in Fig. 3(b), all the threshold powers for $\omega_l = 130$ μm are higher than that for $\omega_l = 105$ μm. At an incident pump power of 18.6 W, the maximum order of HG modes was only up to $\text{TEM}_{6,0}$ in this condition according to the larger SRS threshold power. It is obvious that a smaller cavity mode size is necessary to generate higher-order HG beams at the Stokes wavelength. We anticipate that the order of HG modes can be much higher as the spot radius of the laser beam can be much smaller.

Furthermore, the comparison of the SRS output performances between the composite and normal crystals for the thermal

$$A_R(\delta; a) = \frac{(1 + a^2)\pi\omega_l^2 \exp\left[\frac{2\delta^2}{1 + a^2}\right]}{\sum_{k=0}^{n} \frac{2^k k!}{2^{2n+1} n!}\left(\frac{2a^2}{1 + a^2}\right)^k \left\{\sum_{j=0}^{[(n-k)/2]} \binom{n}{k + 2j}\frac{(k+2j)!}{k!j!}\left(\frac{a^2 - 1}{a^2 + 1}\right)^j H_{n-k-2j}\left(\frac{2\delta}{1 + a^2}\right)\right\}^2} \quad (2)$$
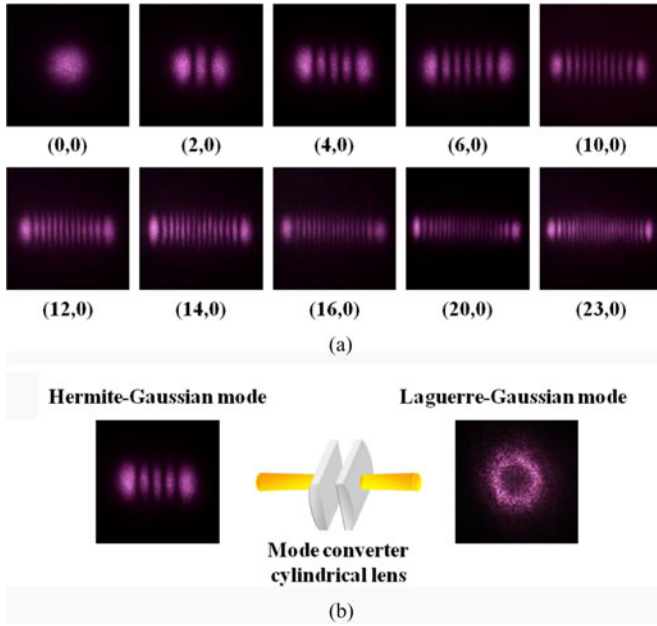
Fig. 5. (a) Experimental patterns of high-order HG $TEM_{n,0}$ modes observed by a CCD camera. (b) An optical vortex beam converted from the HG $TEM_{4,0}$ mode by a $\pi/2$ cylindrical-lens mode converter.

loading was researched. Under the same circumstance, the roll-over phenomenon in the SRS output power for the normal $Nd:YVO_4$ crystal was experimentally observed at an incident pump power of 17.6 W. At the roll-over threshold, the SRS output power for the $TME_{0,0}$ mode was measured to be 360 mW. The maximum order was only $TEM_{4,0}$ with the SRS output power of 100 mW at the same incident pump power. It indicates that the gain medium with diffusion bond can effectively reduce the thermal induced cavity loss to achieve much higher output power and maximum order. Perhaps a double-end diffusion-bonded $Nd:YVO_4$ crystal might be more useful to obtain the better SRS output performance since less thermal loading in the gain medium.

The experimental patterns of the high-order HG $TEM_{n,0}$ modes at the first Stokes wavelength of 1176 nm recorded by a CCD camera are shown in Fig. 5(a). These HG modes had high temporal stability at a fixed incident pump power. As increasing the incident pump power, we need to finely adjust the laser cavity to keep the stability. By measuring the beam waist and the divergence angle, the value of the M_x^2 factor for each high-order HG mode can be determined to confirm the purity of the mode. The experimental results of the M_x^2 factor increases step-wise with the off-axis displacement as a function $M_x^2 = 2n + 1$ which are good agreement with the ideal values. As these high-order HG beams passed through a rotatable $\pi/2$ cylindrical-lens mode converter outside the laser cavity, high-order optical vortex beams at the Stokes field were created subsequently. The focal length of the two identical cylindrical lenses was $f = 25$ mm, and the distance was separated by $\sqrt{2}f$. The experimental pattern for a high-order optical vortex beam transformed from a HG $TEM_{4,0}$ mode is shown in Fig. 5(b). It can be seen that the high-order optical vortex beams at the Stokes wave are success-

fully generated from a self-Raman laser with off-axis pumping by converting high-order HG modes through an extra-cavity mode converter.
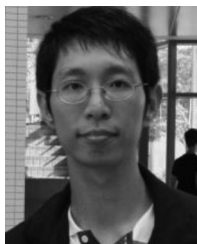
IV. CONCLUSION

In summary, we have successfully created high-order HG beams from a $YVO_4/Nd:YVO_4$ self-Raman laser with an off-axis pumping scheme. We experimentally explore the performance for the generation of the high-order HG modes at the fundamental wavelength of 1064 nm. At an incident pump power of 2.5 W, all the average output powers of high-order HG modes can be higher than 1.0 W for the order up to $TEM_{34,0}$. Next, we theoretically verify the feasibility of generating high-order HG modes at the Stokes field by off-axis pumping. In the Stokes field, the SRS output powers for the $TEM_{n,0}$ modes decrease slowly only in the low-order regime at an incident pump power of 18.6 W. Under the same pump power, the maximum order can be up to $TEM_{28,0}$. With the assistance of a simple $\pi/2$ cylindrical-lens mode converter, high-order optical vortex beams at the Stokes wavelength are created by transforming high-order HG modes into LG modes.

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