Watt-Level 1173 nm Laguerre-Gaussian Mode Generation From a Self-Raman $Nd:GdVO_4$ Laser

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(Invited Paper)

***Abstract*—We demonstrate a high power (watt-level) self-Raman $Nd:GdVO_4$ Laguerre-Gaussian (LG) mode laser by employing an off-axis needle-pumping geometry. The system selectively produces right- or left-handed LG modes by adjusting the off-axis displacement of the pump beam relative to the laser cavity. The maximum output power of the generated 1173 nm LG beam (corresponding to the first-Stokes emission of from the 882 cm^{-1} Raman shift) reaches 1.2 W for an absorbed pump power of 8.6 W. Furthermore, the system enables the generation of a watt-level bottle beam, formed by the coherent superposition of Gaussian and radial LG modes.**

***Index Terms*—Bottle beam, Laguerre-Gaussian mode, off-axis needle-pumping geometry, self-raman $Nd:GdVO_4$ laser.**

I. Introduction

LAGUERRE-GAUSSIAN (LG) modes [1]–[4] are eigen modes of the paraxial wave equation in cylindrical coordinates. They possess several unique properties, such as an annular spatial intensity profile with a central dark spot, unique handedness, and orbital angular momentum (OAM), $\ell\hbar$ (where ℓ is termed a topological charge), owing to their helical wavefront. Their unique properties have resulted in their use across a wide range of applications, including optical tweezers/manipulators which impart orbital motion to trapped particles [5]–[8], quantum/optical telecommunications with high data capacity [9]–[12], nano/micro-fabrication of helical structures [13]–[15], and optical vortex laser induced forward transfer (LIFT), a process in which a single optical vortex pulse is used for nozzle-free printing of pico-liter-scale donor microdots with an extremely long working distance [16]–[18]. To increase the diversity of applications for these unique laser beams, it is highly desirable to generate LG laser outputs having wavelength-versatility.

Stimulated Raman scattering (SRS) [19]–[23] is a well-known third-order nonlinear process used for wavelength conversion of laser beams. It is a process which, has the capacity to convert existing laser wavelengths to other more difficult to generate wavelengths. One example of such is for the conversion of common neodymium-based wavelengths at $\sim$ 1064 nm to wavelengths in the 1.2 μm region, the so-called 'water window' which are of extreme importance in advanced bio-medical applications [24]–[27]. Of particular interest is the application of so-called self-Raman laser crystals such as neodymium ions doped vanadates [28]–[31] and double tungstates [32]–[35], which double as both the laser gain medium and the Raman conversion crystal and enable the development of ultracompact wavelength-versatile solid-state lasers.

Self-Raman LG mode lasers have previously been constructed using a variety of approaches, perhaps the most common being via the use of a cavity mirror with an engineered damage spot which forces the laser to oscillate on LG modes [36], [37]. However, severe thermal effects can significantly impact the reliable power scaling of these cavity designs and degrade the beam quality of the generated LG modes at high pump powers (M^2>2.5 at the absorbed pump power of 6.8 W) [36].

An alternative approach to generating LG modes from a self-Raman $Nd:GdVO_4$ laser is through the use of a shaped pump beam which utilizes an axicon lens and an objective lens [38]. This system design enables the selective generation of a first-order LG mode with zero-OAM, resulting from the incoherent superposition of left- and right-handed LG modes. The system can generate LG mode emission at wavelengths of either 1108 nm or 1173 nm individually, or 1108 nm and 1173 nm simultaneously merely by changing the alignment of the laser cavity output coupler. However, the output powers in [38] were limited to 49.8 mW and 133.4 mW at the wavelengths of 1108 nm and 1173 nm respectively even at a relatively high pumping level (absorbed pump power of $\sim$ 5.7 W).

An off-axis pumping approach has also been well established in moderate gain 1 μm lasers [39], [40]. It allows the effective achievement of spatial intensity matching between the higher-order mode (vortex mode) and the pumped region,

Manuscript received 10 June 2022; revised 20 July 2022; accepted 23 July 2022. Date of publication 27 July 2022; date of current version 3 April 2023. This work was supported in part by the Kakenhi Grants-in-Aid under Grants JP16H06507, JP17K19070, and JP18H03884, in part by the Japan Society for the Promotion of Science (JSPS), and in part by the Japan Science and Technology Agency (JST) Core Research for Evolutional Science and Technology under Grant JPMJCR1903. *(Corresponding author: Takashige Omatsu.)*

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Color versions of one or more figures in this article are available at https://doi.org/10.1109/JLT.2022.3194186.

Digital Object Identifier 10.1109/JLT.2022.3194186

thereby resulting in selective generation of the $LG_{0,\pm 1}$ modes in end-pumped solid-state laser systems. Also, the astigmatic thermal lens effects in the gain medium break the cylindrical symmetry of the cavity, so as to control the handedness of the generated LG modes.

However, there are no demonstrations of the vortex mode generation by employing this technique in such CW self-Raman lasers with extremely low gain and high Q cavity lasers.

The Poincaré sphere, which maps right- and left-handed circular polarization states onto its north and south poles, is commonly used to visualize the polarization states of monochromatic light. Analogous to this, the equivalent orbital Poincaré sphere (eOPS) [41]–[43], in which its north and south poles represent LG modes with OAM $= \pm \ell \bar{h}$, can be used as a means of visualizing different states of light; that is orbital Poincaré (OP) modes can be represented as a superposition of the two poles.

The first-order OP modes $OP(\theta, \phi)$ are expressed by

$$OP(\theta, \phi) = LG_{0,+1} \cos\theta \cdot e^{-i\phi} + LG_{0,-1} \sin\theta \cdot e^{i\phi}, \quad (1)$$

where $LG_{0,\pm 1}$ are the orthogonal LG modes with topological charges of ± 1, and θ and ϕ are the polar and azimuthal angles of eOPS, respectively. The states of right- and left-handed ($LG_{0,\pm 1}$) vortex modes are represented at the two poles.

Recently, we and our co-workers demonstrated a diode-pumped Pr^{3+}:YLF first-order orbital Poincaré mode laser utilizing an off-axis optical needle pumping geometry, in which a combination of off-axis pumping configuration and lenses with strong spherical aberration produced an off-axially-localized 'hotspot' with a long confocal length and contained a significant fraction of the optical energy [44]. This system enabled the production of a variety of structured modes, such as Hermite-Gaussian (HG), LG and Herimite-Laguerre-Gaussian (HLG) modes, each of which could be represented on a first-order equivalent orbital Poincaré sphere (eOPS). This system also generated emission even at 523 nm from a laser line which has low emission cross-section.

In this paper, we report on the first demonstration (to the best of our knowledge) of a high power (watt-level) continuous-wave self-Raman Nd:$GdVO_4$ LG mode laser through the application of the above mentioned off-axis optical needle pumping geometry. This work also includes exotic results that the generated fundamental and Stokes outputs possess the same handedness.

A maximum LG mode output power of 1.2 W was obtained for an absorbed pump power of 8.6 W (pump power of 10.1 W), corresponding to a conversion efficiency of 14.0%. These are the highest powers (to the best of our knowledge) obtained from an LG mode self-Raman laser. We demonstrate that the handedness of the fundamental (1063 nm) and Stokes (1173 nm) vortex outputs can be controlled through the off-axis displacement of the pump beam. Furthermore, the system enables the generation of a versatile range of structured laser modes which can be mapped on the OPS.

Interestingly, the system, when utilizing an on-axis pumping arrangement, also produces a watt-level 1173 nm bottle beam which has a three-dimensional dark core, and is formed by the coherent superposition of Gaussian and radial LG modes.

II. Experiments

Fig. 1(a) is a schematic showing the layout of the experimental laser system. The self-Raman laser crystal was an *a*-cut 0.3 at.% Nd:$GdVO_4$ crystal with an aperture of 3×3 mm^2 and a length of 10 mm. It was wrapped with indium foil and mounted in a water-cooled copper block and its surface temperature was maintained at 19°C. The plane input facet of the self-Raman crystal was used as the laser cavity input mirror. It was coated for high reflectivity (R $>$ 99.99%) across the range 1033-1263 nm and high transmission (T $>$ 99.933%) for 879 nm. A concave output coupler (OC) was used with the self-Raman crystal to form the laser cavity, coated for high reflectivity (R $>$ 99.99%) for 1063 nm, and 1% transmission at 1173 nm. The laser cavity length was fixed at 15 mm.

A fiber-coupled 879 nm laser diode (*n*Light element *e*03) with a core diameter of 200 μm and a numerical aperture of 0.22 was used as the pump source, and its output was collimated and then focused by two plano-convex lenses (L_1, $f = 50$ mm; L_2, $f = 25$ mm) onto the input facet of the self-Raman laser crystal. These lenses were oriented so that the convex surfaces of the lenses were facing to incident pumping beam, and the strong spherical aberration induced by the two plano-convex lenses produced a 'needle-like' pump beam (with a bright spot diameter of $\sim$ 97 μm and a confocal length of $\sim$1 mm (in the crystal)). This is shown in Fig. 1(b). In contrast, in a conventional pumping geometry, where the convex surfaces of the lens L_1 and L_2 are facing each other, a focused spot with a diameter of $\sim$115 μm and a confocal length of $\sim$0.5 mm is produced, as shown in Fig. 1(c). The absorption efficiency of the pump beam in the crystal was measured to be $\sim$ 85%.

The OC of the laser was mounted on a three-dimensional translation stage to enable off-axis pumping wherein displacements of the OC along the *x* and *y* axes altered the spatial overlap of the pump beam and cavity modes resulting in the generation of a range of spatial modes, such as HG, LG, and HLG modes [45]. With this system, the fundamental output wavelength was 1063 nm and the corresponding Stokes output occurred at 1173 nm. The spectral output of this system is shown in Fig. 1(d). The collinear fundamental and Stokes beams were spatially separated using a transmitting grating (200 lines/mm), and they were characterized using a laser beam profiler (Spiricon SP620U).

III. Result and Discussion

When the system was operated using an on-axis pumping configuration (in which all components were aligned collinearly), the system produced Bessel beam-like fundamental and Stokes outputs with multiple rings. Interestingly, when focused, the Stokes output was transformed and exhibited an annular spatial form with a dark core in the near field, manifesting as a 'bottle beam' with a three-dimensional dark core surrounded by a bright region along with the propagation direction of the optical axis.

The experimentally and theoretically modelled spatial form of this 'bottle beam' as it propagates through space is shown in Fig. 2 . The maximum output power of the Stokes output was

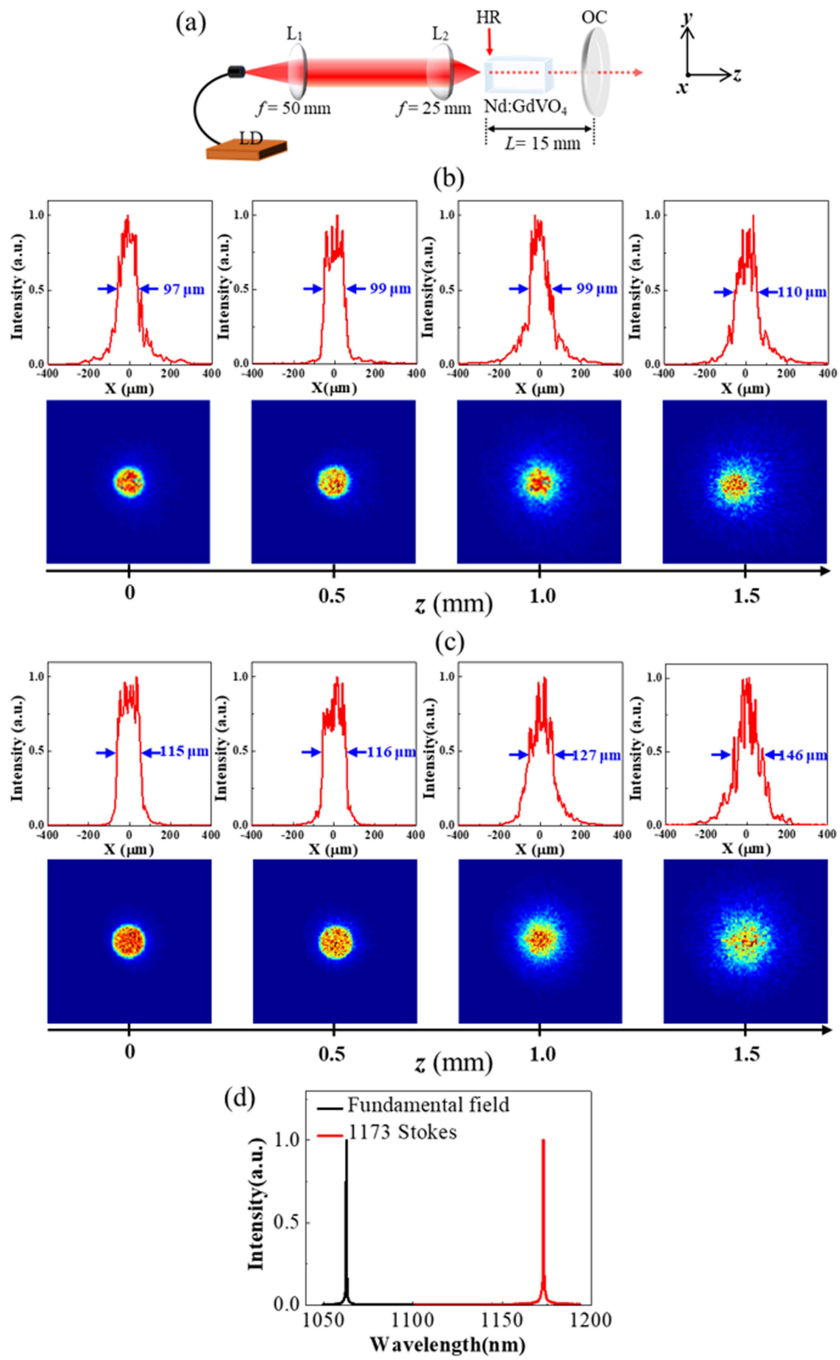

Fig. 1. (a) Schematic showing the experimental setup for direct generation of structured light beams from a self-Raman Nd: $GdVO_4$ laser. LD: 879 nm fiber-coupled laser diode; L_1: collimating lens ($f = 50$ mm); L_2: spherical planoconvex lens ($f = 25$ mm); HR: high-reflection coating for 1033-1263 nm; OC: output coupler. (b) Spatial profiles of the 'needle-like' pump beam as a function of position inside the crystal. (c) Spatial profiles of the pump beam as a function of position inside the crystal when using a conventional pump lens arrangement. (d) Normalized laser spectrum measured at the fundamental (1063 nm) and Stokes (1173 nm) fields.

measured to be 0.96 W at an absorbed pump power of 9.8 W (pump power of 11.5 W).

The generation of 'bottle beams' has been demonstrated in both degenerate and frequency-doubled hemispherical cavities, in which Gaussian and higher-order transverse modes operate at the same frequency [46], [47]. The ultrahigh-Q self-Raman laser in this experiment also facilitates coherent coupling between Gaussian and several radial LG ($\ell = 0$, $p \neq 0$) modes leading to 'bottle beam' generation. The 'bottle beam' $u(r, z)$ can be expressed by the following equation,

$$u(r,z) = \sum_p a_p LG_{p,0}(r)\, e^{i(2p+1)\tan^{-1}\left(\frac{z}{z_R}\right)} \tag{2}$$

where r and z are the radial and propagation coordinates, p is the radial index, a_p is the relative amplitude of the $LG_{p,0}$ mode $\left(\sum_p |a_p|^2 = 1\right)$, and z_R is the Rayleigh length ($z_R \sim$ 63 mm in this experiment). The 'bottle beam' is thus produced

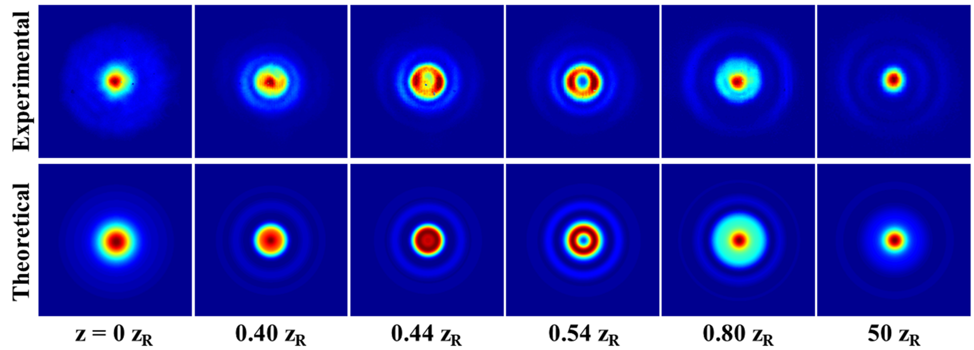

Fig. 2. Plots showing the experimental and theoretically-calculated transverse spatial forms of the generated bottle beam at different longitudinal positions relative to the Rayleigh length (z_R). The output power of the generated bottle beam was then measured to be 0.96 W at an absorbed pump power of 9.8 W.

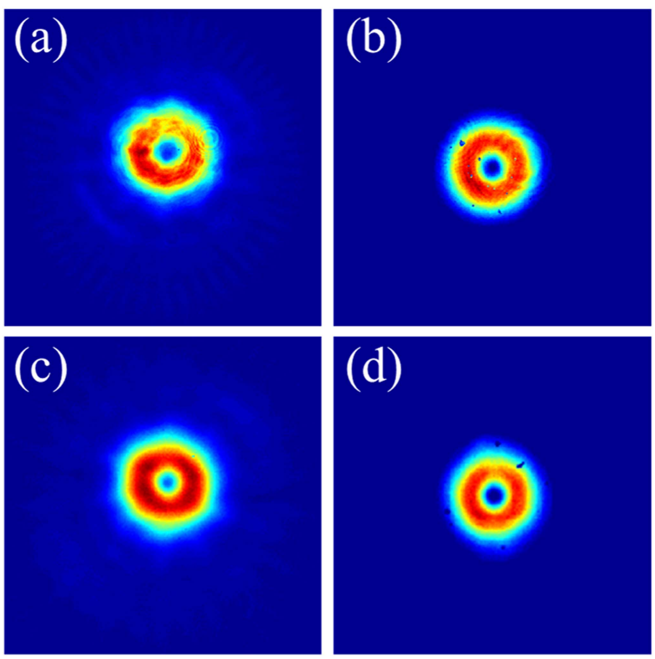

Fig. 3. Plots of the experimentally-derived spatial intensity profiles of (a) the fundamental (1063 nm), and (b) the Stokes (1173 nm) outputs in the near-field. Corresponding far-field patterns of (c) the fundamental and (d) the Stokes outputs. The absorbed pump power was fixed to be 8.6 W. The fundamental and Stokes output powers were then measured to be 23 mW and 1.2 W, respectively.

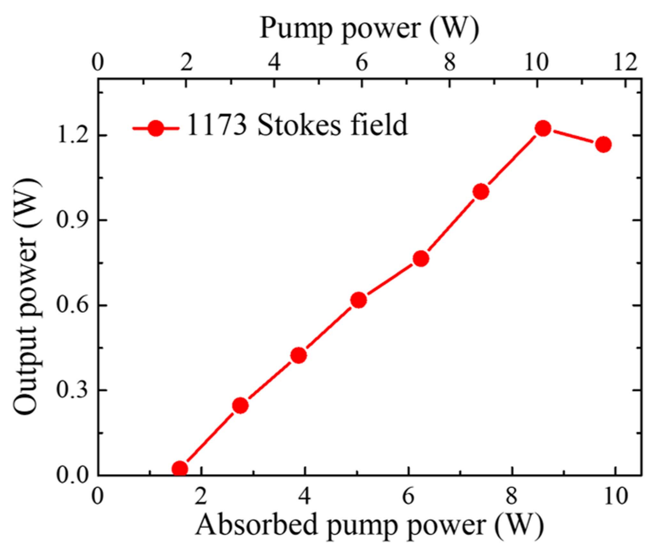

Fig. 4. Plot of the power-transfer curve of the Stokes LG output power as a function of the absorbed pump and pump powers.

through the coherent coupling of $LG_{p,0}$ modes with different Gouy-phase. In fact, simulations, in which a central dark core with three high-intensity rings appear at the longitudinal position of $z = 0.54\, z_R$, support the experimentally observed bottle beam, as shown in Fig. 2. The relative amplitudes of $LG_{p,0}$ modes with radial indices of $p = 0$, 2, and 4 were then fixed to be 0.7, 0.49, and 0.52, respectively. This demonstrates a compact and efficient method, by which watt-level bottle beams with high beam quality can be generated from a self-Raman laser configuration combined with an on-axis needle pump beam arrangement.

When the off-axis displacement of the OC from the optical axis of the cavity was appropriate ($\Delta x = \pm 31.5\ \mu$m, $\Delta y = \pm 22.5\ \mu$m), the fundamental output (1063 nm) exhibited a mixed mode profile with a central dark core, and was comprised of several high-order modes; this form was maintained for all input pump levels. For this fundamental wavelength spatial form, the 1173 nm Stokes output exhibited perfect 1st order LG mode ($|\ell| = 1$) properties in both the near and far-fields even at the high pump levels (absorbed power ~9.8 W, pump power 11.5 W). This was due to beam cleanup effects, as reported in prior publications [45], [48]. The maximum Stokes output power was measured to be 1.2 W, corresponding to an optical conversion efficiency of 14.0% and a slope efficiency of 16.7% at an absorbed pump power of 8.6 W. These values are the highest, to the best of our knowledge, obtained from a diode-pumped self-Raman, LG mode laser. It should be noted that the Stokes output rolled over for absorbed pump powers of > 8.6 W (pump powers of >10.1 W) owing to thermal issues in the self-Raman laser crystal. The thermal lensing power (focal length) in the system is estimated to have reached up ~110 m^{-1} (~0.9 cm) at a maximum absorbed pump level (8.6 W), this being calculated using the model of Innocenzi, in which the pump beam exhibits a Gaussian spatial form [49]. Heat loading in the crystal due to the quantum defect between the pump and Stokes photons was assumed to be ~0.24. This theoretical analysis of the thermal lensing effects might

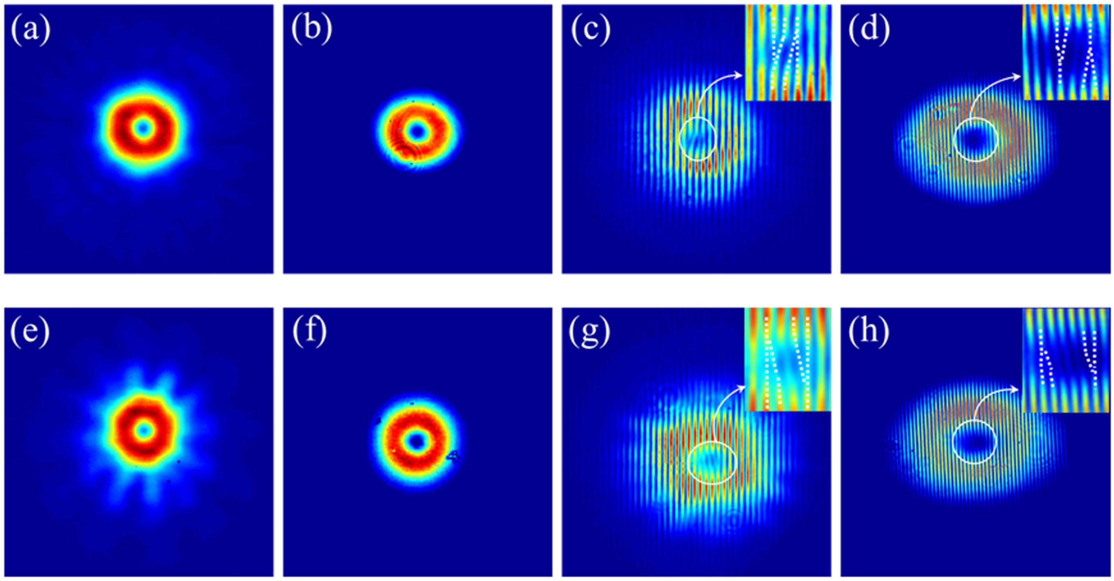

Fig. 5. Plots of experimentally determined spatial intensity profiles (a,b) and corresponding self-interference fringes (c,d) of the fundamental (a,c) and Stokes (b,d) outputs at the displacement $\Delta x = 31.5\mu$m of OC along x-direction. The spatial intensity profiles (e,f) and corresponding self-interference fringes (g,h) of the fundamental (e,g) and Stokes (f,h) outputs after shifting the OC at the displacement Δx = -31.5μm of OC along x-direction.

be slightly overestimated, however, it correlates well with the experimental observations.

A self-referenced and laterally-sheared interferometer was constructed in order to analyze the wavefronts of the fundamental and Stokes outputs, similar to that described elsewhere [45], [50]. The fundamental and Stokes outputs were found to possess first-order optical vortex characteristics with $\ell = +1$ (-1), as evidenced by a pair of upward (downward) and downward (upward) Y-shaped fringes. Control of the handedness of the fundamental and Stokes outputs was achieved through appropriate manipulation of the off-axial displacement of the OC towards opposite x and y directions, as detailed in our prior publications [45]. We observed that the Stokes output typically carried the same handedness as that of the fundamental output, as shown in Fig. 5(d), (h). This is explained by the fact that in general, the Raman gain is determined by the spatial intensity profile of the fundamental output. Therefore, direct OAM transfer of the fundamental output to the Stokes output is inherently inhibited [36]. In contrast, we believe that our experimental observations are indicative of the handedness of the fundamental and Stokes outputs being determined by the off-axis pumping in conjunction with thermal lensing effects breaking the cavity-symmetry.

Through appropriate off-axis displacements of the OC, we were able to map the experimentally generated HG and HLG modes onto various equator and meridian positions of an OPS, as shown in Fig. 6. For each of these experimentally generated modes, the output Stokes laser power was in the range 0.9∼1.0 W. It should be noted that while each of the modes mapped onto the OPS could be faithfully generated, it did require very precise cavity alignment due to the severe thermal issues manifesting in the self-Raman laser crystal. We believe that such watt-level OPS mode sources operating in the 1.2 μm region have potential for the development of advanced bio-medical technologies and applications.

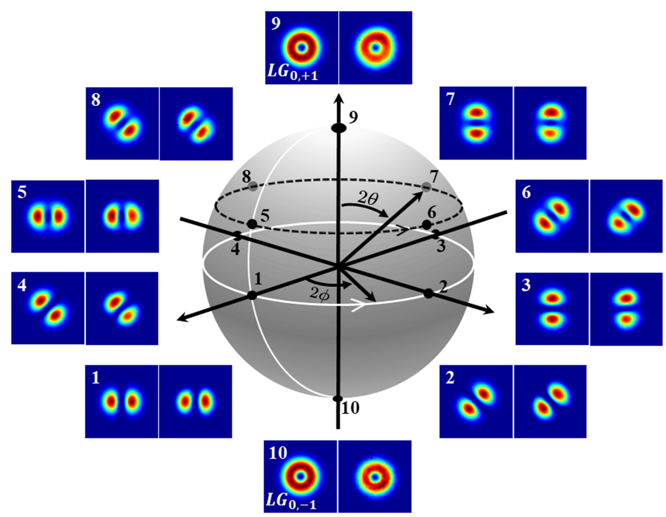

Fig. 6. Plots of the spatial intensity profiles of both experimental (right images) and theoretical modes (left images) generated at a wavelength of 1173 nm, mapped onto the PS. The numbers indicate the positions of each beam on the OPS.

IV. Conclusion

We have successfully demonstrated, for the first time to the best of our knowledge, the direct generation of watt-level 1173 nm LG mode emission with $\ell = \pm 1$ from a diode-pumped, self-Raman Nd:$GdVO_4$ laser utilizing an off-axis optical needle pumping configuration. Notably, the generated fundamental and Stokes wavelength outputs carried the same handedness due to breaking of the cavity-symmetry induced by the off-axis pumping. A maximum 1173 nm LG mode output power of 1.2 W was achieved for an absorbed pump power of 8.6 W (pump power of 10.1 W). Additionally, it was possible to produce a 'bottle beam' output with a power of 0.96 W at a wavelength of 1173 nm by using an on-axis pumping geometry. We anticipate that further power scaling of the system will be possible by improving the heat management characteristics of the system and optimization of the pump system. Importantly, we believe that this work is a significant step towards novel laser sources which operate in the 1.2 μm 'water window' region, which may enable new, advanced bio-medical applications. We also anticipate that by combining this laser design with intracavity sum frequency mixing, wavelength-versatile LG mode lasers in the visible region will also be developed.

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