# High power Er:YAG laser with radially-polarized Laguerre-Gaussian ($LG_{01}$) mode output

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**Abstract:** A simple method for conditioning the pump beam in an end-pumped solid-state laser to allow direct excitation of the first order Laguerre-Gaussian doughnut ($LG_{01}$) mode is reported. This approach has been applied to a hybrid (fiber-laser-pumped) Er:YAG laser yielding 13.1 W of continuous-wave output at 1645 nm in a radially-polarized $LG_{01}$ doughnut beam with beam propagation factor ($M^2$) < 2.4 for 34 W of incident pump power at 1532 nm. The corresponding slope efficiency with respect to incident pump power was 48%. The prospects of further power scaling and improved laser performance are discussed.

**OCIS codes:** (140.0140) Lasers and laser optics; (140.3070) Infrared and far infrared lasers; (140.3500) Lasers, erbium; (140.3510) Lasers, fiber; (140.3580) Lasers, solid-state

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## 1. Introduction

Laser beams with a ring-shaped intensity profile, sometimes referred to as hollow laser beams or doughnut beams, have applications in a number of areas including laser drilling and writing [1, 2], optical manipulation of particles [3, 4], trapping and guiding of atoms [5, 6] and lithography [7]. Not surprisingly, methods for generating hollow laser beams have been the subject of much research over the years. Simple beam shaping schemes (e.g. based on axicons [8, 9] or hollow-core fibers [10]) provide a relatively straightforward route to a doughnut beam, but at the expense of a significant degradation in beam quality and brightness, hence limiting applicability. A more attractive route is to generate a Laguerre-Gaussian mode with a ring-shaped intensity profile (e.g. $LG_{0n}$ mode). This can be achieved using external beam-shaping arrangements (e.g. based on spatial light modulators [11, 12], computer-generated holograms [13], a pair of cylindrical lenses [14, 15]) to transform a Hermite-Gaussian mode ($TEM_{0n}$) into the required Laguerre-Gaussian mode. Scaling to high powers via this route is rather challenging due to power handling limitations of the beam transforming optics and the difficulty in scaling power for single mode $TEM_{0n}$ lasers. Alternatively, hollow Laguerre-Gaussion beams can be generated directly within the laser itself, for example, by exploiting bifocussing [16, 17] or via the use of intra-cavity mode discriminating components (e.g. by using diffractive optical elements [18, 19]). However, to date these approaches have suffered from rather low efficiency and limited flexibility due to pump-power dependent resonator configurations or the need for additional relatively high-loss intra-cavity components.

Here we report an alternative and very simple strategy for directly generating a high quality $LG_{01}$ mode in a laser, which is especially well-suited for hybrid (fiber-laser-pumped) bulk solid-state laser architectures [20, 21] and hence offers the prospect of very high average output power in continuous-wave (cw) and pulsed modes of o`peration. Using this approach, we have successfully operated an Er:YAG laser, in-band pumped by an Er,Yb fiber laser, with a high quality radially-polarized $LG_{01}$ mode output. The laser produced 13.1 W of output at 1645 nm for 34 W of incident pump power at 1532 nm. To the best of our knowledge, this is the first demonstration of a high-power end-pumped Er:YAG laser operating on the $LG_{01}$ mode.

## 2. Experiment and results

Our approach makes use of a simple, low-loss fiber-based beam shaping element to re-format the output beam from the cladding-pumped fiber laser pump source into a ring-shaped pump beam whilst maintaining reasonably good beam quality. The ring-shaped pump beam is tailored to spatially-match the intensity distribution for the first-order Laguerre-Gaussian mode ($LG_{01}$) in the laser medium of a bulk laser resonator with the result that lasing occurs preferentially on the $LG_{01}$ mode since it has the lowest threshold. The experimental set-up for the hybrid Er:YAG laser is shown schematically in Fig. 1. The pump beam was provided by a high-power cladding-pumped Er,Yb fiber laser constructed in-house. The latter comprised a

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~2.5 m length of double-clad fiber with a 30 µm diameter (0.22 NA) Er,Yb co-doped phospho-silicate core surrounded by a 400 µm diameter D-shaped pure silica inner-cladding. The latter was surrounded by a low refractive index (n≈1.375) polymer coating giving the inner-cladding pump guide a calculated numerical aperture of ~0.49. Operation at the absorption peak in Er:YAG at 1532 nm was achieved with the aid of a wavelength-tunable external cavity with wavelength dependent feedback provided by a Volume Bragg Grating (VBG). The VBG had a peak reflectivity of 95% and a full-width at half-maximum (FWHM) reflection bandwidth of 0.5 nm. The Er,Yb fiber laser yielded a maximum power of 78 W at 1532 nm with a linewidth of ~0.2 nm (FWHM) in a slightly multimode beam with $M^2$ ~5. At this power level, the fiber laser was prone to damage so, in order to ensure reliable operation, the laser was operated at power levels below 50 W. Further details of the Er,Yb fiber laser pump source can be found in Ref. 22.

To produce the required ring-shaped pump beam profile, the output from the Er,Yb fiber laser was launched into the solid glass portion (inner-cladding) of a simple capillary (hollow-core) fiber of length, 50 cm. The capillary fiber was fabricated in-house and had pure silica inner-cladding of diameter, 400 µm with a 100 µm diameter air-hole in the center (see the upper-left picture in Fig. 1). The capillary fiber was coated with a low refractive index (n=1.375) fluorinated polymer outer-cladding giving a calculated NA of 0.49 for the inner-cladding waveguide. The launching efficiency was ~94%. The upper-right picture in Fig. 1 shows the transmitted (ring-shaped) near-field output beam profile recorded with a Pyrocam III camera (Spiricon Inc.). The beam propagation factor ($M^2$) for the transmitted pump beam was measured to be ~51 and hence was degraded by a factor of ~10 compared to the incident pump beam in accordance with expectations. The extent to which pump beam quality is degraded by the capillary fiber depends on the input pump beam dimensions and beam divergence, and on the fiber design. Further optimization of the capillary fiber design in conjunction with the use of a single-mode Er,Yb fiber pump laser should yield a substantial improvement in transmitted pump beam quality. One important prerequisite for preferential lasing on $LG_{01}$ mode is that there should be negligible diffraction spreading of the pump beam over the length of the pump absorption region in the Er:YAG rod to ensure that the ring-shaped pump beam profile is preserved and hence spatial-mode-matching to the $LG_{01}$ mode is maintained. Therefore, by setting the Rayleigh range of the pump to be equal to the absorption length ($1/\alpha_p$) for the pump, we obtain the following lower limit for the pump beam radius:

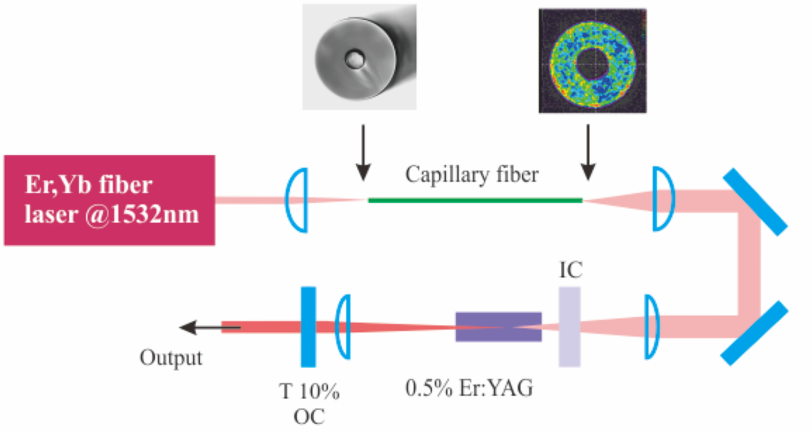

Fig. 1. Schematic diagram of the Er:YAG laser resonator. The pictures show the cross-section of the capillary fiber (upper-left) and the near-field beam profile for the pump beam exiting the capillary fiber (upper-right).

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$$w_p \geq \sqrt{\left(\frac{M^2\lambda}{\pi n\alpha_p}\right)} \qquad (1)$$

where $\alpha_p$ is the absorption coefficient for the pump. This, in turn, imposes a lower limit on the laser mode size and threshold pump power.

A simple two-mirror cavity configuration was employed for the Er:YAG laser comprising a plane pump in-coupling mirror (IC) with high reflectivity (>99.8%) at the lasing wavelength (1617–1646 nm) and high transmission (>95%) at the pump wavelength (1532 nm), an antireflection-coated plano-convex lens of focal length, 350 mm, and a plane output coupler (OC) with 10% transmission at the lasing wavelength. An Er:YAG crystal with a low Er concentration (~0.5 at.%) and length, 29 mm was used as the gain medium. Both end faces of the crystal were antireflection coated at the pump and lasing wavelengths and it was mounted in a water-cooled aluminum heat-sink maintained at 17°C positioned in close proximity to the input coupler. The absorption length for pump light at 1532 nm in the Er:YAG crystal was measured to be ~10 mm, hence from Eq. (1) the minimum pump beam waist radius that can be used was estimated to be ~370 µm. The distance between the output coupler, lens and input coupler were selected to give a calculated mode radius for the fundamental ($TEM_{00}$) of ~300 µm in the Er:YAG crystal. The radial intensity distributions for the $LG_{01}$ mode, $I_{0,1}(r)$ and the $TEM_{00}$ mode, $I_{0,0}(r)$ are related via the expression [23]:

$$I_{0,1}(r) = \left(\frac{2P_L}{\pi w^2}\right)\cdot\left(\frac{2r^2}{w^2}\right)\exp\left(-\frac{2r^2}{w^2}\right) = \left(\frac{2r^2}{w^2}\right) I_{0,0}(r) \qquad (2)$$

where $r$ is the radial coordinate in the transverse plane, $w$ is the radius of the $TEM_{oo}$ mode (i.e. at $1/e^2$ of its peak on-axis intensity) and $P_L$ is the total power in the mode. The beam radius for the $LG_{01}$ mode is $\sqrt{2}$ times larger than the $TEM_{00}$ mode [23], so the pump beam exiting the capillary fiber was magnified by a factor of 2.25 using a simple telescope to yield a ring-shaped pump beam with a waist outer radius of ~450 µm and an inner ‘hole’ radius of ~113 µm inside the Er:YAG rod, thus satisfying the condition set by Eq. (1).

The laser output power as a function of incident pump power is shown in Fig. 2(a). The laser yielded 13.1 W of output at 1645 nm at the maximum available incident pump power of 34 W. The corresponding slope efficiency with respect to incident pump power was 48%. The threshold pump power was measured to be 5.8 W, which is in close agreement with the calculated value of 5.2 W. It should be pointed out that the threshold pump power for the $LG_{01}$ mode is ~2.2 times larger than for the $TEM_{00}$ mode with a spatially-matched ‘top-hat’ pump beam due to the larger pump beam area for the ring-shaped pump beam required to excite the $LG_{01}$ mode. The output beam profile was monitored as a function of laser power with the aid of a pyroelectric detector 2D array (Pyrocam III). Figure 2(b) shows the beam profiles at low power (3 W) and high power (13 W) confirming the axially-symmetric ring-shaped nature of the output beam. The measured beam propagation factor ($M^2$) for the output beam increased slightly from ~1.9 to ~2.4 with increasing pump power indicating that there is very little thermally-induced beam distortion. The calculated $M^2$ parameter for a perfect $LG_{01}$ mode is 2 [23] and hence is in close agreement with our measured values for $M^2$ confirming that laser mode excited was indeed the $LG_{01}$ mode. Further confirmation was obtained by

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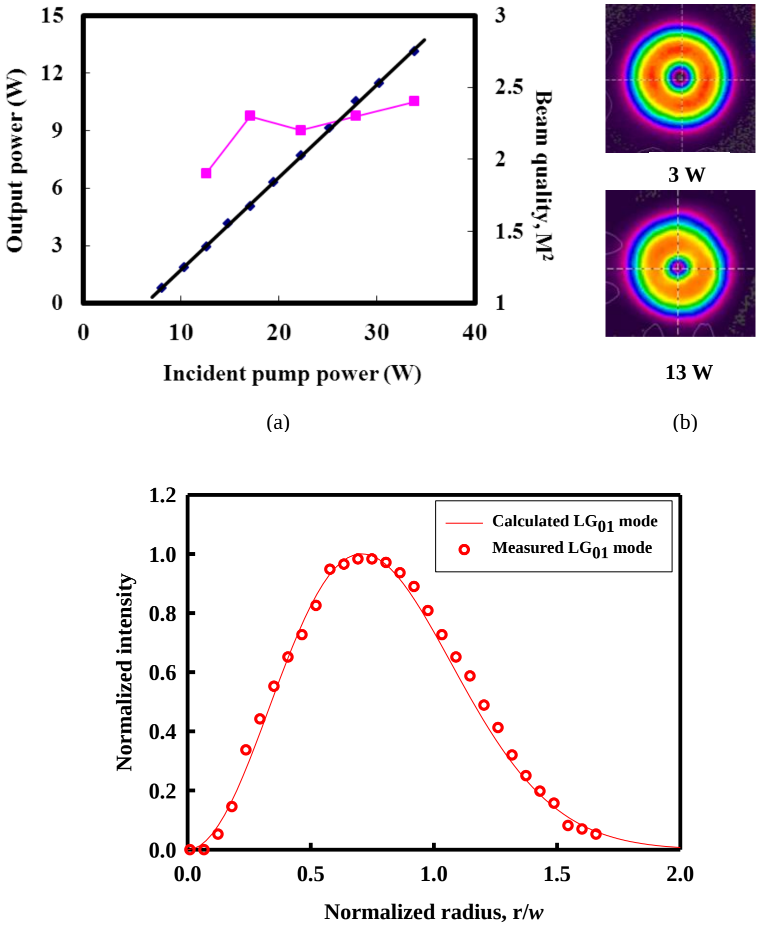

(a)

(b)

(c)

Fig. 2. (a) Er:YAG laser output power and measured beam propagation factor ($M^2$) as a function of incident pump power and (b) the output beam profiles monitored by a Pyrocam III camera. (c) The calculated and measured transverse intensity distributions for the $LG_{01}$.

noting that the measured transverse intensity as a function of radial position is in close agreement with the theoretical transverse intensity profile (Fig. 2(c)).

The polarization state of the output beam was investigated with the aid of the Glan-Taylor calcite polarizer on a rotation stage. Figure 3(a) shows that the magnified (relay-imaged) output beam profile for different angular positions of the polarizer indicating that the laser output was radially-polarized. The polarization purity was investigated by measuring the intensity as a function azimuthal angle. The results (plotted in Fig. 3(b)) show a cosine-squared dependence of measured intensity as expected for radially-polarized light. The extinction ratio (i.e. radial polarization / azimuthal polarization) was found to be >98%. The underlying mechanism for preferential lasing with radial polarization is attributed to thermally-induced bifocussing. This results in slightly different thermal lens focal lengths [24] and hence slightly different laser mode sizes for radial and azimuthal polarization states. As a consequence, one polarization state (in this case the radial polarization state) has a slightly larger mode radius and a better spatial overlap with the ring-shaped inversion distribution. The net result is that the radial polarization has a lower threshold and hence reaches threshold first, saturating the inversion and preventing the azimuthal polarization state from lasing. In this way, the resonator can be designed to select either the radial or azimuthal polarization without having to resort to using a resonator design that is unstable for one polarization. In the present arrangement the output power was limited by the maximum available pump power and there was no evidence of thermally-induced roll-over in output power. Thus, scaling to higher powers should be possible via the use of a higher power Er,Yb fiber pump laser in combination with a better optimized and lower-loss capillary fiber.

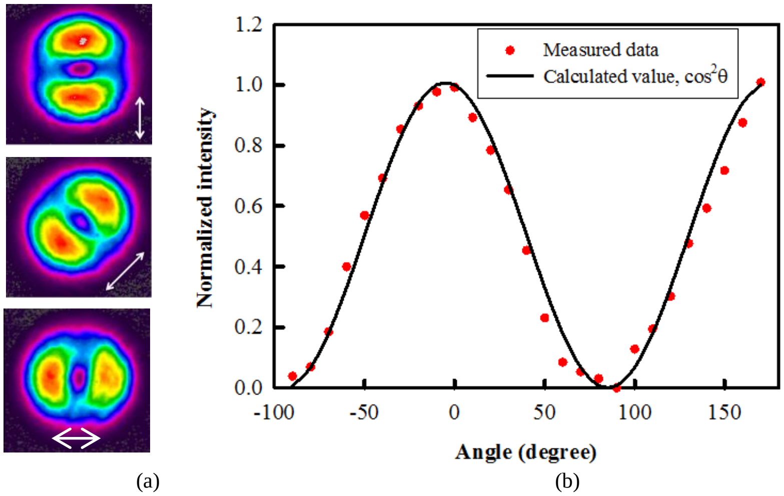

Fig. 3. (a) Relay-imaged output beam profiles for different angular positions of the polarizer. The arrow shows the polarizer transmission direction. (b) The normalized azimuthal intensity as a function of polarizer angle.

## 3. Conclusions

In summary, we have demonstrated a novel method for selectively exciting lasing on the Laguerre-Gaussian $LG_{01}$ doughnut mode in an end-pumped solid-state laser. This approach has been applied to a hybrid Er:YAG laser, in-band pumped by an Er,Yb fiber laser, yielding 13.1 W of cw output at 1645 nm in a high quality, radially-polarized $LG_{01}$ mode with slope efficiency of 48%. Further optimization of the laser design and pump delivery fiber in combination with the use of a higher power Er,Yb fiber pump laser is expected to yield a significant increase in output power. This approach for generating hollow ($LG_{01}$) beams offers many attractions over existing techniques and is particularly well-suited to low quantum defect hybrid (fiber-laser-pumped-bulk-laser) configurations operating in the wavelength regimes around 1.6 µm and 2 µm [25]. The combination of high efficiency, power scalability and flexibility in mode of operation afforded by this technique should benefit a range of applications requiring high power hollow laser beams.

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