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

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Abstract: A simple method to allow direct excitation of the first-order Laguerre-Gaussian mode has been applied to a hybrid Er:YAG laser. The laser yielded 13.1W of radially-polarized LG_{01} output at 1645nm for 34W of pump power.

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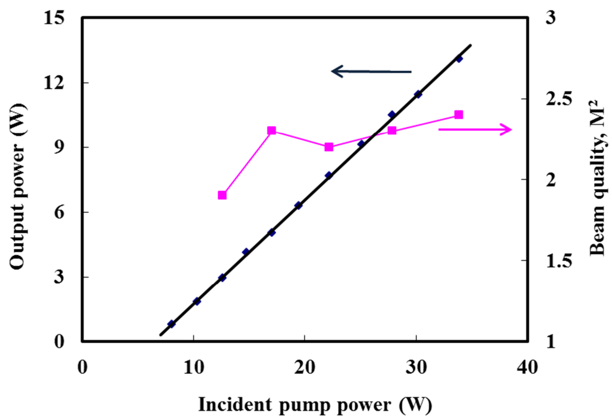
Laser beams with a ring-shaped intensity profile, sometimes referred to as hollow laser beams or donut beams, have applications in a number of areas including laser drilling and writing [1], optical manipulation of particles [2], trapping and guiding of atoms and lithography. Not surprisingly, methods for generating hollow laser beams have been the subject of much research over the years. Simple beam shaping schemes (e.g. based on axicons [3] or hollow-core fibers) provide a relatively straightforward route to a donut 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_{01} mode). This can also be achieved using external beam-shaping arrangements (e.g. based on spatial light modulators, computer-generated holograms, a pair of cylindrical lenses [4]) 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 [5] or via the use of intracavity mode discriminating components (e.g. by using diffractive optical elements [6]). 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 [7] and hence offers the prospect of very high average output power in continuous-wave (cw) and pulsed modes of operation. 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.

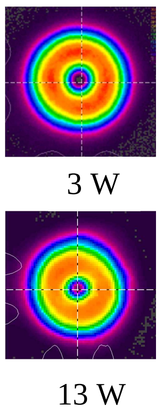
Our approach makes use of a simple beam shaping element to re-format the output beam from the cladding-pumped fiber laser pump source into a ring-shaped pump beam whilst maintaining reasonably good beam quality. The ring-shaped pump beam is tailored to spatially-match the intensity distribution for the 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 pump beam was provided by a high-power cladding-pumped Er,Yb fiber laser constructed in-house. The latter comprised a ~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. 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. 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 $M^2 \sim 5$. The output from the Er,Yb fiber laser was shaped to the required ring-shaped beam profile and was launched into the Er:YAG crystal. A simple two-mirror cavity configuration was employed for the Er:YAG laser comprising a plane pump in-coupling mirror 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 with 10 % transmission at the lasing wavelength. An Er:YAG crystal with a low Er concentration (~0.5 at.%) and length, 29mm 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 laser output power as a function of incident pump power is shown in Fig. 1(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. The output beam profile was monitored as a function of laser power with the aid of a pyroelectric detector 2D array (Pyrocam III). Fig. 1(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 [8] and hence is in close agreement with our measured values for M^2 confirming that laser mode excited was indeed the LG_{01} mode. The polarization state of the output beam was investigated with the aid of the Glan-Taylor calcite polarizer on a rotation stage. Figure 3 shows that the magnified (relay-imaged) output beam profile for different angular positions of the polarizer indicating that the laser output was radially-polarized.

This approach for generating Laguerre-Gaussian (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. 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.



(a)



(b)

Fig. 1. (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.

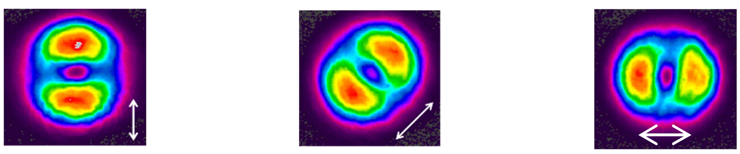


Fig. 2. Relay-imaged output beam profiles for different angular positions of the polarizer. The arrow shows the polarizer transmission direction.

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