Coupling Efficiency of Laguerre-Gaussian Modes in a Hollow Fiber

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Why use Laguerre Gaussian modes?

- Using the special characteristics of Optical vortex beams, which have **orbital angular momentum (OAM)**, can make it useful in multiple applications.
- To use these applications in a experiment the beam may have to be transported, and therefore would need a optical fiber to do so, that was efficient.
- Experiments in which OAM could be used included optical tweezers and optical communication[1].

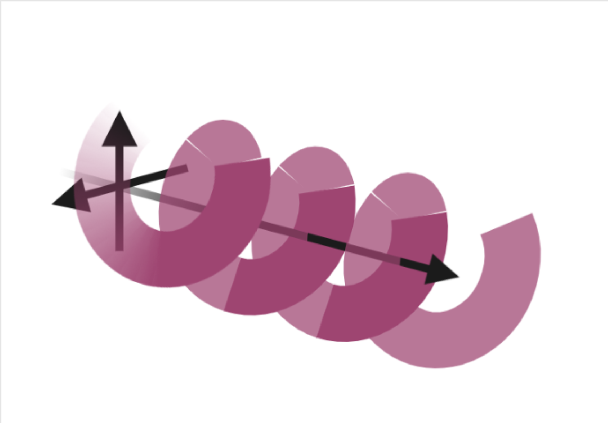

Figure 1. A beam showing orbital angular momentum, by the phase changing with the angle around the axis of propagation.

How to generate LG modes from HG

- **Hermite-Gaussian (HG) and Laguerre-Gaussian (LG) modes** come from a basis set of functions created by solving the Paraxial wave equation in Cartesian and polar coordinates, respectively [2].

$$\varepsilon_p^l = \frac{1}{w(z)}\sqrt{\frac{2p!}{n(|l|+p)!}}e^{l(2p+|l|+1)\varphi(x)}(\frac{\sqrt{2}r}{w(z)})^{|l|}L_p^{|l|}(\frac{2r^2}{w(z)^2})e^{-i\frac{r^2}{q(z)^2}+il\theta}$$

$$\varepsilon_{nm} = E_0\frac{w_0}{w(z)}H_n(\sqrt{2}\frac{x}{w(z)})e^{-\frac{x^2}{w(z)^2}}H_m(\sqrt{2}\frac{y}{w(z)})e^{-\frac{y^2}{w(z)^2}}e^{-i[kz-(1+n+m)\varphi+\frac{k(x^2+y^2)}{2R(z)}]}$$

- The LG beam can be made of a base of HG modes superimposed to each other.
- In our case the open cavity He-Ne laser creates a HG mode at an angle to begin with, which is also the base of two separate HG modes

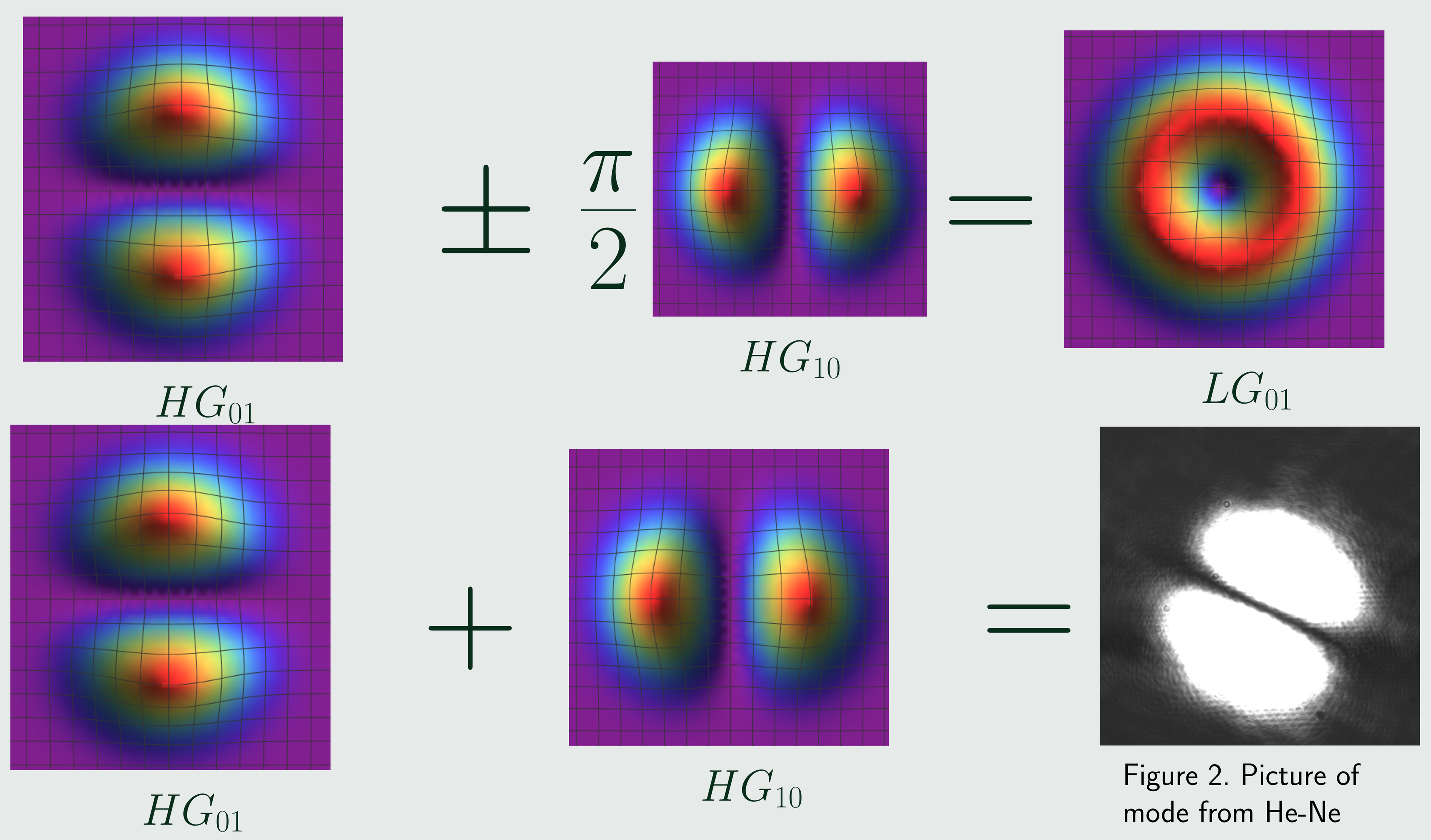

Figure 2. Picture of mode from He-Ne

- By sending a HG beam into the phase converter, of either one or two cylindrical lens the Gouy phase is used to create a LG beam [2].

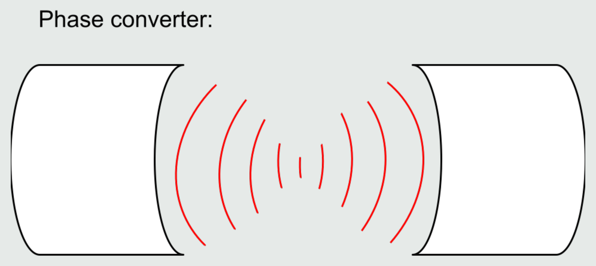

Figure 3. Two lens focuses a light beam between where the red lines represents the wavefront of the beam. It is clear that closer to lens the wave front is curved but at the focuses the wavefront changes shape to a line, this phase change is the Gouy phase.

Experimental Setup

- The starts with a open cavity He-Ne Laser, with an adjustable out coupler and mode selector to create the HG modes.
- A spherical lens is used to focuses light into a phase converter which is made up of one or two cylindrical lens.
- The light is then collimated and then using two mirrors is sent into a hollow fiber of a 1mm diameter.

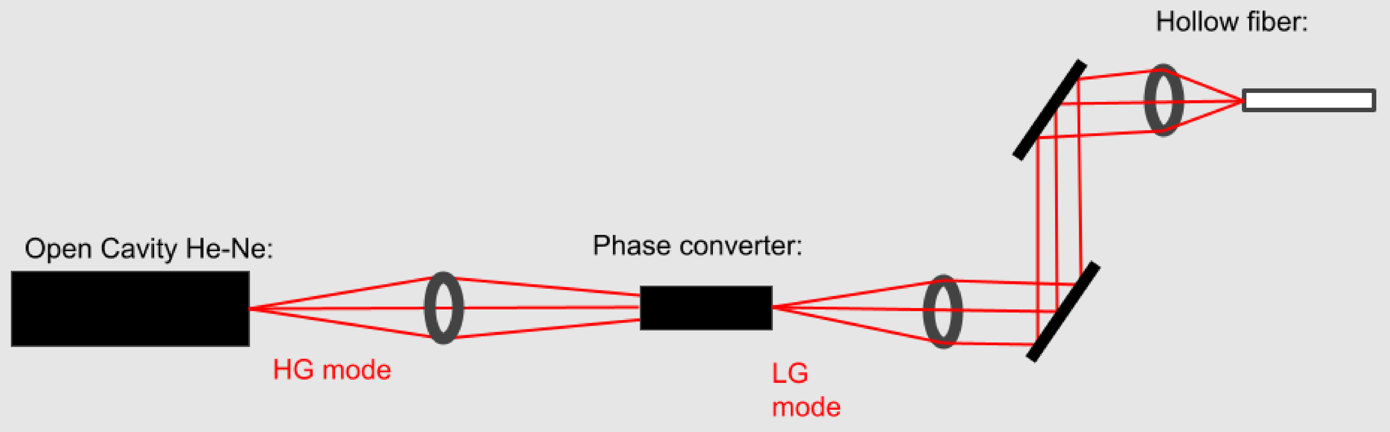

Figure 4. Experimental Setup used to create LG beams and also fiber couple, with both a single and double lens phase converter.

Not Completely LG

- Because the double lens phase converter was not aligned perfectly, it was found that there was still HG mode leaking through.
- Taking a line out of light this is made clear by the two peaks resembling a HG mode.

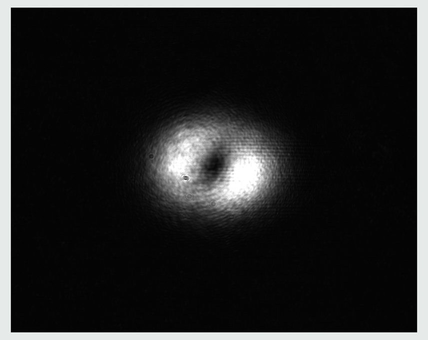

Figure 5. LG beam profile from two lens phase converter.

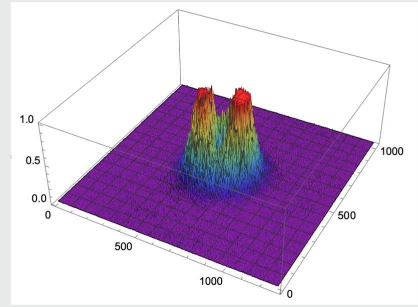

Figure 6. 2-d line out from LG beam profile.

- By simulating the 2-d line-out it was easy to see the weight of the two components of HG_{10} and HG_{01} were not being weighted evenly.

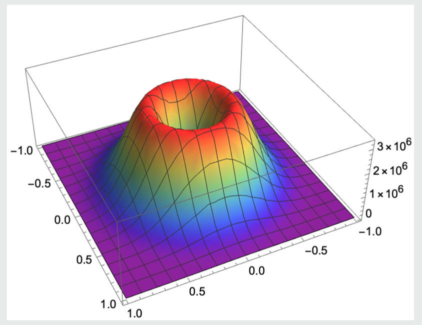

Figure 7. $LG_{01} = HG_{01} \pm \frac{\pi}{2}HG_{10}$

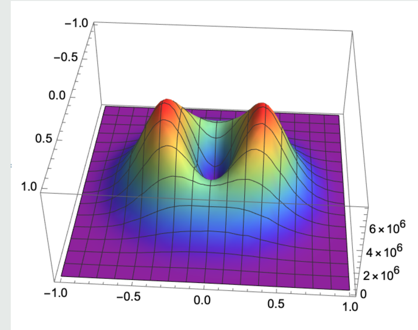

Figure 8. $LG_{01} = (1.5)HG_{01} \pm \frac{\pi}{2}HG_{10}$

Figure 9. LG beam profile from single lens phase converter.

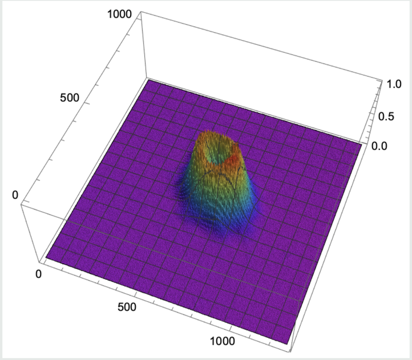

Figure 10. 2-d line out from LG beam profile.

- Next trying the single lens converter, does create a more visual looking LG beam but gives the overall shape a distortion.

Hollow fibers Coupling

- To couple efficiently into a hollow fiber the ratio between the beam waist and the diameter of the fiber is essential[3].
- To find this ratio the wave function of the LG beam while at it's waist is normalized.This normalization constant can then be used to find the ideal ratio.

$$\psi_p = \sqrt{\frac{2}{\pi}}\frac{1}{w_o}L_p(\frac{2r^2}{w_o^2})e^{\frac{-r^2}{w_o^2}} \qquad A_p = \sqrt{\frac{2}{\pi}}\frac{1}{w_o}\int_0^a J_0(\frac{u}{a}r)L_p(\frac{2r^2}{w_o^2})e^{\frac{-r^2}{w_o^2}}2rdr$$

- Following this idea, a knife edge measurements was done at at the focus point of a lens. For 1mm fiber sizes the ideal waist was .25mm

Wave-guide Theory

- Once inside a optical fiber geometric optics break down and wave-guide theory is needed describe the propagation of light[4].
- Signal mode fiber: only will support, while have a smaller difference of index of refraction between the cladding and core.
- Multi-mode fiber: is made with a larger difference of index of refraction, light can then excite a multiple modes

Conclusion

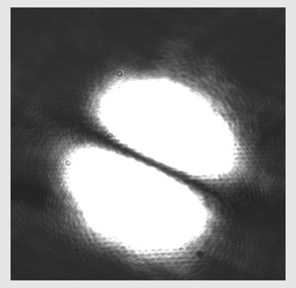

Figure 11. HG_{01} before hollow fiber

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Figure 12. HG_{01} after hollow fiber

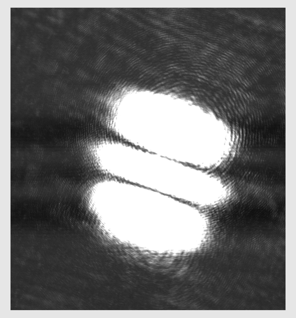

Figure 13. HG_{02} before hollow fiber

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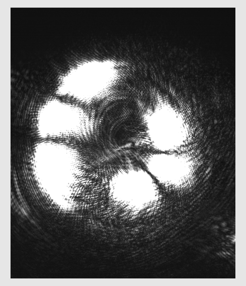

Figure 14. HG_{02} after hollow fiber

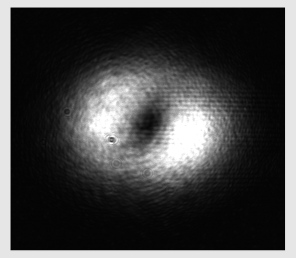

Figure 15. LG beam from double lens converter

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Figure 16. LG beam from double lens converter after fiber

- The shape of the HG modes looks similar to the non-pure LG mode. This originally gave the indication that the phase converter was not working correctly.

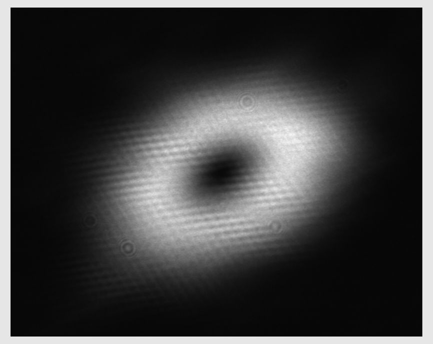

Figure 17. LG_{01} before hollow fiber

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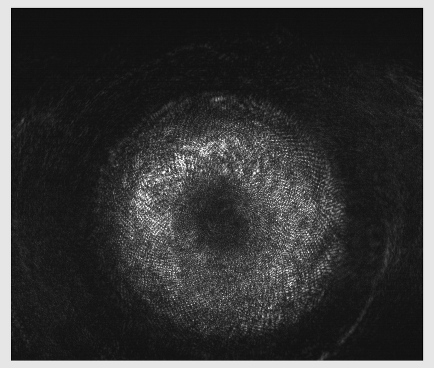

Figure 18. LG_{01} after hollow fiber

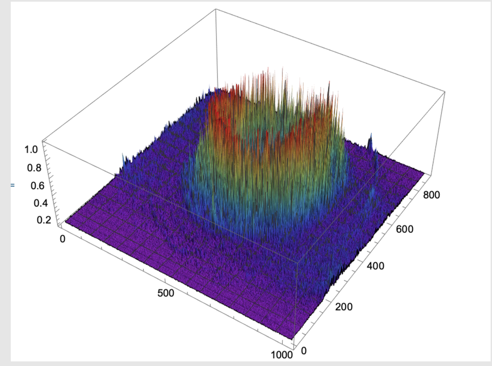

Figure 19. 2-d line-out of LG beam through hollow fiber

- With the single lens converter the beam profile from the hollow fiber does have the same distribution as a HG mode.
- The finial 2-d line-out shows the LG distribution is similar to the simulated LG shape. This shows the hollow fiber can keep the mode of the LG beam.

References

[1] Shen, Y., Wang, X., Xie, Z. et al. Optical vortices 30 years on: OAM manipulation from topological charge to multiple singularities. Light Sci Appl 8, 90 (2019).
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Acknowledgements

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