Optical aberrations in a spinning pipe gas lens

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Abstract: If a heated pipe is rotated about its axis, a density gradient is formed which results in the pipe acting as a graded index lens. In this study we revisit the concept of a spinning pipe gas lens and for the first time analyse both the wave propagation of optical fields through the lens, and determine the optical aberrations introduced by the lens to the laser beam. We show that such lenses are highly aberrated, thus having a deleterious effect on the laser beam quality.

OCIS codes: (350.5340) Photothermal effects, (010.7350) Wave-front sensing, (220.1010) Aberrations (global)

References and links

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2. M. M. Michaelis, M. Notcutt, and P. F. Cunningham, "Drilling by a Gas Lens Focused Laser," Opt. Commun. **59**, 369–374 (1986).
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1. Introduction

The device discussed in this paper is a heated steel pipe made to rotate (spin) about its axis, thus forming a graded refractive index profile across the diameter of the pipe. Under certain conditions this profile leads to wave guiding, and with judicious choice of pipe length, an output beam that is converging in space can be obtained. When this happens, the system is seen to act as a lens, and is referred to as a spinning pipe gas lens (SPGL). The SPGL was invented by Martynenko [1] in 1975 and subsequently gained popularity as a device for high power laser delivery. It has been used for focusing high power lasers [2] and as a telescope objective [3]. To date there has been no attempt to quantify the quality of such lenses: there is no information on how well such lenses perform, if they have a deleterious affect on the beam quality factor of the focused light, or what optical aberrations are imparted to the propagating wavefront. Rather the lens is assumed to be perfect, while the propagating field is always assumed to be best described by the ray approximation. Mention is only made of so–called 'near diffraction limited' spots [4], but this is insufficient information to propagate the resulting beam.

In this paper we revisit the SPGL with the aim of characterizing its performance in the context of modern laser beam propagation language. In section (2) we briefly introduce the concept of the SPGL, and then present experimental data on the measured optical aberrations introduced by the SPGL in section (3). We report for the first time the impact such lenses have on the beam quality factor (M^2) of the focused laser beam, and indicate what aberrations are contributing to this increase in M^2. Our results show that while the hitherto approximation of a quadratic refractive index is indeed accurate for describing the lensing, there are higher order aberrations introduced that have a material impact on the efficacy of the SPGL as a laser beam delivery element.

2. Spinning pipe gas lens

From the well–known Gladstone–Dale law one notes that the refractive index of air increases with decreasing temperature; light passing through a medium with a temperature gradient will tend to bend towards the colder air, giving rise to the well–known 'mirage' effect. The SPGL aims to exploit this property of air by creating a temperature gradient, and hence a refractive index gradient, where all the light is bent towards the central axis of the pipe, thereby creating a lensing environment. This is achieved through heating the outside walls of the pipe and then spinning the pipe about its axis.

If a horizontal stationary steel pipe is heated to a suitably high temperature, convection currents result in the higher density air being predominantly at the bottom of the pipe with the lower density air predominantly above. When the pipe is rotated about its axis, the heated layer of air near the pipe wall rotates and is expelled from the pipe through its end face. The expelled heated air is replaced by cooler air drawn in along the pipe axis, which is in turn heated and expelled. Under steady–state conditions the air near the axial region of the pipe is therefore cooler and denser than the air near the pipe wall. These arguments have been confirmed for the first time by a full Computational Fluid Dynamics (CFD) model of the transient behaviour of the SPGL from a fluid flow perspective. A fully transient solution is presented in which the pipe is spun from a heated steady–state buoyancy driven solution and held at speed until steady–state is reached.

Some of the results of this study are shown in Figs. 1 and 2. The CFD model shows that there is a very slow velocity field near the ends of the pipe, with a cross–sectional view of an end section of the SPGL shown in Fig. 1. The velocity vector field shows both the direction and the speed of the air in this section, illustrating the exchange with the surroundings as explained above. The velocity flow remains slow but becomes more uniform towards the middle of the pipe (along its length). Because of the slow flow, the thermal boundary layer is able to extend to the centre of the pipe in the radial direction over the entire heated section of the pipe. This large boundary layer is what gives rise to the density profile across the pipe diameter, which is mostly stable with a small unstable region near the pipe wall.

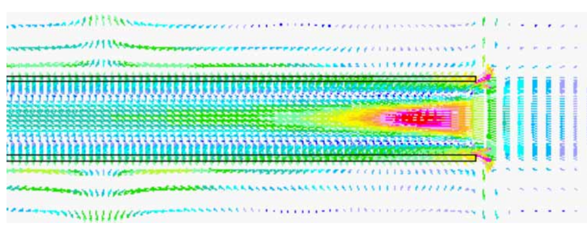

Fig. 1. A cross–section of a SPGL showing the velocity distribution of the gases as the warmer gas near the wall escapes, and is replaced by the cool air which enters along the axis. (Fig 1 Movie [5.3 MB])

A radial cross–section near one of the end faces shows the density profile created from heating and from spinning, as calculated using the CFD model. In Fig. 2(a) we note that after heating, convection currents establish an asymmetric density profile, while rotating the pipe results in symmetry of the density profile, as shown in Fig. 2(b).

In previous studies it has been assumed that as the gas lens is rotated, the medium inside the pipe achieves a graded refractive index distribution following a parabolic profile given by:

$$n(r) = n_0 - \tfrac{1}{2}\gamma^2 r^2 , \quad (1)$$

where n_0 is the refractive index along its axis, r is the radial distance from the axis and γ is a constant given by the parameters of the SPGL [4]. This implies that only defocus (curvature)

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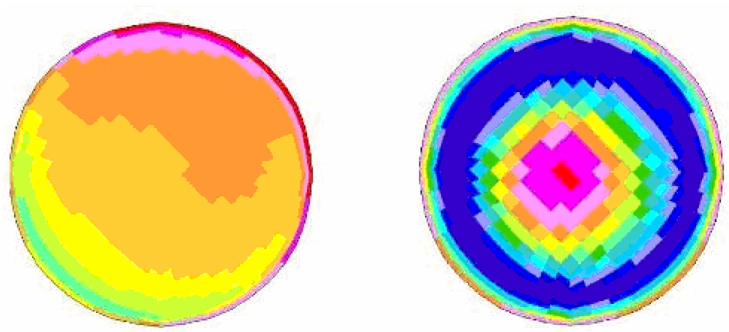
is introduced to the wavefront of the passing beam. What has not been addressed in the literature is the type and magnitude of the other aberrations (if any) that are introduced. This is an important consideration if high power lasers are to be used with the lens, as laser brightness (proportional to the square of the inverse of the laser beam quality) would certainly decrease if the lens was highly aberrated.



(a) (b)

Fig. 2. Cross–sectional density profiles of an SPGL showing: (a) the initial state after heating, and (b) the rotating steady–state near the end face of the pipe, with high density centre (red) and low density edges (blue). (Fig 2 Movie [4 MB])

3. Experimental setup and results

The experimental setup is as shown in Fig. 3. A HeNe laser beam (Thorlabs, model HRP 020) was attenuated through neutral density filters and then expanded by a $\times 10$ beam expander to a collimated beam of 5.48 mm $1/e^2$ radius. The beam was then steered into an SPGL of length 1.43 m and internal diameter 36.6 mm. The SPGL was heated using resistive heater tape which was wound along a central length of 0.93 m, leaving the end–sections of length 25 cm each unheated. The wavefront of the exit beam was measured with a Shack–Hartmann wavefront sensor (Wavefront Sciences, model CLAS 2D), with a 69×69 lenset array, placed immediately after the exit face of the SPGL. Care was taken to place the wavefront sensor on a separate optical table from the one on which the gas lens was mounted in order to minimise the impact of vibrations due to the spinning of the pipe. The laser beam was carefully aligned to make sure that its axis and that of the pipe coincided before heating the pipe.

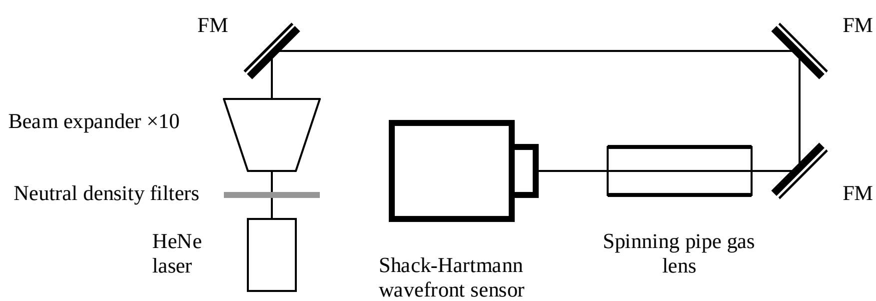


Fig. 3. Experimental set–up. (FM = Flat mirror).

The pipe was heated to predetermined wall temperatures of 351, 373, 400 and 422 K. At each temperature the pipe was rotated from rest to roughly 17 cycles per second (this maximum frequency was limited only by the available equipment and is not a physical limitation of the SPGL), with data collected at intermediate frequency intervals.

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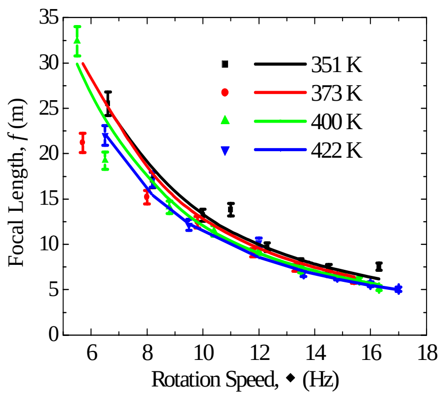
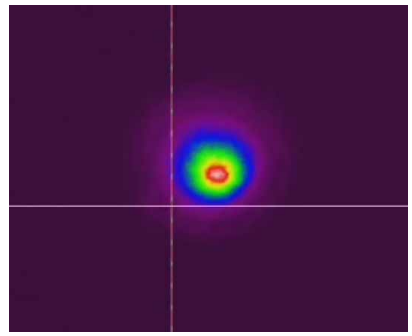
3.1 SPGL lensing

The lensing behaviour of the SPGL is shown in Fig. 4. The inverse relationship between focal length and rotation speed for a given pipe wall temperature is typical of such lenses [4]. At high rotation speeds (ω) and large temperatures (T) the lens is strong, typically in the range of a few meters. The empirical formula for the focal length is found to be $f \sim 5{\times}10^4\ T^{-0.8}\ \omega^{-1.6}$.



(a)

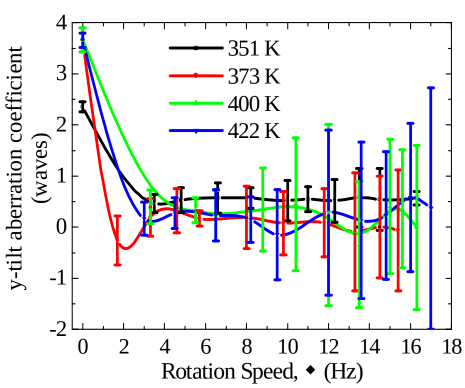


(b)

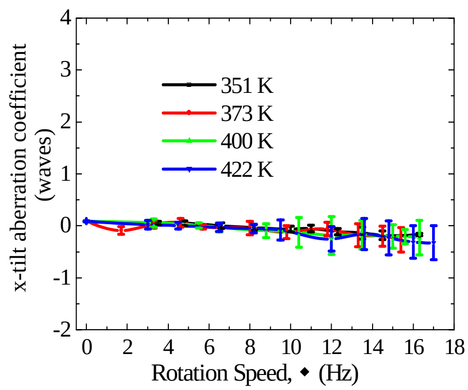
Fig. 4. (a) The focal length of the SPGL as calculated from the optical wavefront and confirmed by inspection, and (b) the intensity distribution during rotation (T = 422 K). (Fig 4b Movie [0.15 MB])

3.2 Aberrations

With the aid of the wavefront sensor we were able to quantify how the lens behaves from an optical aberration perspective. When the pipe is heated but not rotated, the CFD model predicts a density gradient in the vertical (gravitational force) direction, with the more dense gas at the bottom. This is confirmed experimentally through the measurement of a large y–tilt component at $\omega = 0$ for all temperatures. Once the pipe is rotated the density gradient becomes radial and a symmetric density profile is created. Consequently the y–tilt decreases from roughly 4 waves to less than 1 and then remains almost constant, as shown in Fig. 5(a). The x–tilt is very small in comparison to the y–tilt even when heated, and remains almost unchanged during rotation, as expected.



(a)



(b)

Fig. 5. (a) y–tilt and (b) x–tilt.

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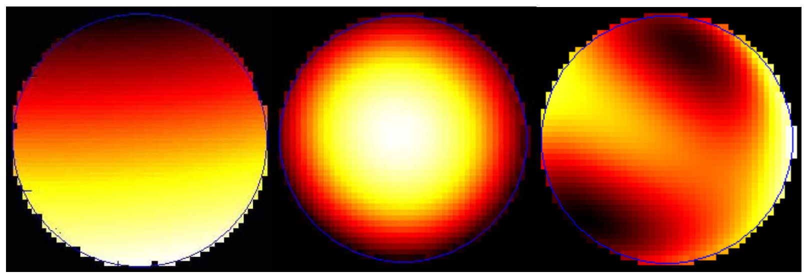
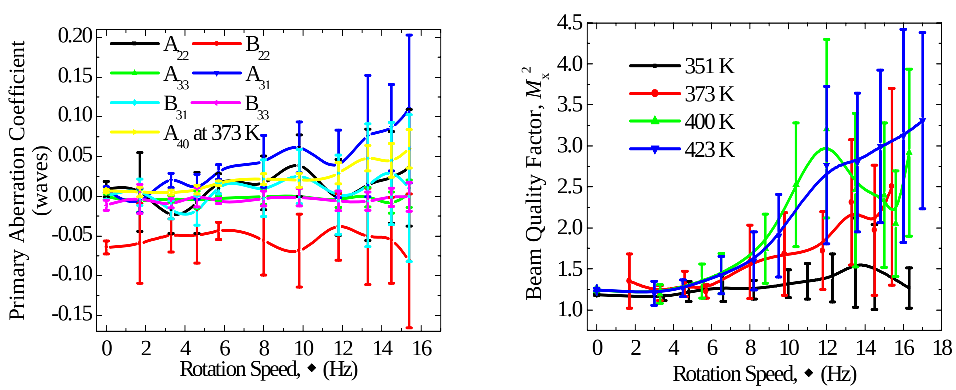
If only defocus and tilt were introduced by the SPGL, then the beam quality factor, M^2, of the laser beam would be unchanged after passing through the lens, since only the wavefront curvature and the direction of propagation would be altered. However, our measurements reveal that higher order aberrations are introduced in such lenses, as shown in Fig. 6. Prior to rotation we note a wavefront with tilt clearly dominating (Fig. 6(a)); on rotation the curvature on the wavefront becomes dominant (Fig. 6(b)), which is responsible for the lensing effect. But if these terms (defocus and tilt) are removed from the wavefront, the higher order aberrations become apparent (Fig. 6(c)).



(a) (b) (c)

Fig. 6. The phase distribution of the laser beam with: (a) no rotation but heated to 422 K, showing tilt; (b) after rotating the SPGL at 17 Hz, showing significant curvature on the wavefront; and (c) same conditions as in (b) but with defocus and tilt removed, revealing the higher order aberrations.

We have decomposed the aberrations into the most significant in terms of magnitude: coma (A_{31} and B_{31}), spherical aberration (A_{40}) and astigmatism (A_{22}, B_{22}, A_{33} and B_{33}) each tending to increase with increasing rotation speed and wall temperature, as shown in Fig. 7(a). Consequently the beam quality factor, M^2, also increases in a concomitant manner, as shown in Fig. 7(b).



(a) (b)

Fig. 7. (a) Higher order aberrations introduced by the SPGL; (b) increase in M_x^2 with rotation speed and temperature as a direct result of the aberrations in (a).

Throughout this paper the error bars on the graphs are used to depict one standard deviation (σ) about the mean (μ) of the sample set, i.e., $\mu \pm \sigma$. In both Figs. 5 and 7 we notice an increase in the standard deviation of the data at strong lensing conditions (high rotation speed and/or high temperature), with smaller standard deviation for weak lensing conditions. This trend is not, however, noticed in the focal length data. The results are also noted qualitatively by observing the focal spot of the beam – strong lenses lead to repeatable focal lengths but poor quality beams showing excessive randomness in the distribution of light at

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the focus. This could possibly be due to mechanical vibrations in the pipe itself, or random mixing of the gases at the various boundary layers in the pipe system. In this context we present a preliminary result from the CFD model, illustrated as an animation in Fig. 8, showing a clear density instability that arises in the transient behaviour of the rotating pipe system at high rotation speeds. Note that in this image the unheated section of the pipe is included on the left of the pipe, with the density cross–section taken at the heated–unheated pipe interface. Since the CFD model includes neither turbulence nor pipe imperfections which might lead to such instability, one must conclude that this is a physical artefact of the fluid dynamics of the rotating system and not an ‘engineering’ problem of imperfect pipes. However, further investigation is required to understand the origin of such instabilities and their impact on the optical quality of the SPGL.

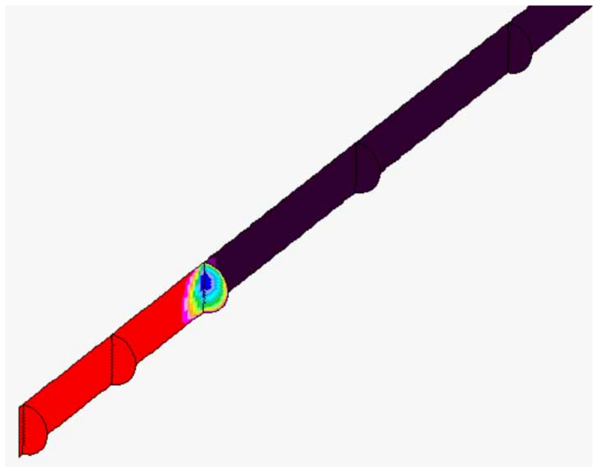

Fig. 8. A CFD model of the SPGL showing the onset of an as yet unknown instability in the density profile. (Fig 8 Movie [1.2 MB])

Using the CFD results and the experimental data, we can now paint a more complete picture of the SPGL: when the SPGL is heated, convection currents are created. The dominant aberration introduced by this process is tilt in the vertical axis (direction of the force due to gravity). As the pipe begins to rotate, axial gas exchange with the atmosphere takes place, introducing a symmetric density gradient and a reduction in tilt: the onset of lensing. However, as the lens strength increases, random gas mixing at the various boundary layers (axial and radial) inside the pipe result in aberrations such as astigmatism, spherical aberration and coma, with a concomitant increase in the beam quality factor, M^2, or equivalently, a worsening of the overall beam quality as the beam deviates from the initial Gaussian profile with no aberration. Furthermore, the variance in almost all the laser beam parameters tends to increase with the strength of the lens, with the exception of the focal length of the lens.

4. Conclusion

We have revisited the SPGL with the aim to apply modern optical techniques to address unresolved issues of this interesting lens, thereby placing the SPGL on a footing that allows an informed decision on its potential efficacy for a particular application. Firstly, we have confirmed the previously held assumption that the rotation removes or at least minimises the distortion due to convection currents. This has been well demonstrated by the decrease in y–tilt upon rotation, and confirmed through a CFD model of the SPGL. Secondly, we have shown how changes (pipe rotation speed and wall temperature) that tend to increase the strength of the lens also tend to increase the higher order aberrations, resulting in a deleterious effect on the beam quality factor of the focussed beam. Would such lenses still find application? We think yes. There is at present very few feasible solutions to the focusing of high power laser systems, and it is quite possible that the loss in beam quality can be compensated for by the increase in transmission power that can be delivered. There is also a need in many delivery systems for long focal length (weak) lenses, for example, in laser propulsion or long range target designating, and this may be the realm where the SPGL has a serious role to play.

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