High power infrared super-Gaussian beams: generation, propagation and application

Neil C. du Preez[a], Andrew Forbes[b,c†] and Lourens R. Botha[b]
[a]SDILasers – Division of Klydon (Pty) Ltd, PO Box 1559, Pretoria 001, South Africa
[b]CSIR National Laser Centre, Box 395, Pretoria 0001, South Africa
[c]School of Physics, University of KwaZulu-Natal, Private Bag X54001, Durban 4000, South Africa

ABSTRACT

In this paper we present the design of a CO_2 laser resonator that produces as the stable transverse mode a super–Gaussian laser beam. The resonator makes use of an intra–cavity diffractive mirror and a flat output coupler, generating the desired intensity profile at the output coupler with a flat wavefront. We consider the modal build–up in such a resonator and show that such a resonator mode has the ability to extract more energy from the cavity that a standard cavity single mode beam (e.g., Gaussian mode cavity). We demonstrate the design experimentally on a high average power TEA CO_2 laser for paint stripping applications.

Keywords: Flat–top beams, resonator modes, diffractive optics, TEA CO_2 lasers, paint stripping

1. INTRODUCTION

There are many applications in which a laser beam with a flat–top intensity profile would be ideal, as compared to a laser beam with a non–uniform energy distribution. Laser based paint stripping is an example of such an application that can benefit from a laser beam with a flat top intensity profile. Standard stable optical resonators will unfortunately not generate such a laser beam as the oscillating mode. Single–mode oscillation would typically be Gaussian in profile, while multimode oscillation might deliver a beam with an averaged flat–like profile in the near field, but would diverge very quickly due to the higher order modes. In addition, if the modes are coherently coupled, then large intensity oscillations could be expected across the beam. Techniques exist to generate flat–top beams external to the cavity, but this is usually at the expense of energy, and almost always requires very precise input beam parameters. A traditional laser resonator configuration is depicted in Fig. 1. It consists of a gain medium inside an optical cavity which is supplied with energy. Usually the cavity consists of two mirrors aligned such that the light passes through the gain medium several times, while traveling between the two mirrors. One of the two mirrors is made partially transparent, and the laser beam is emitted through this mirror (henceforth referred to as the output coupler).

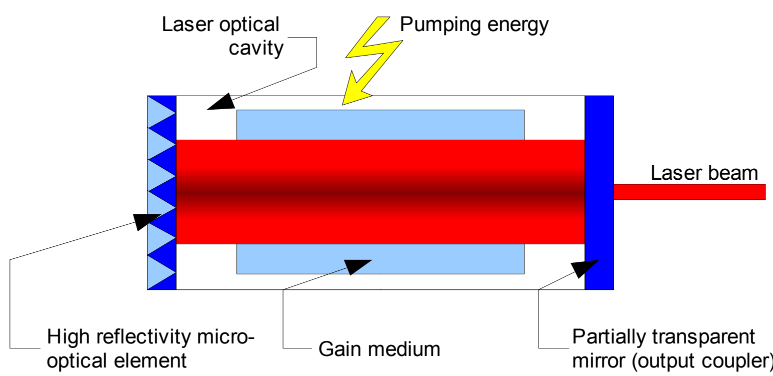


Fig. 1. Laser resonator with a gain medium and a diffractive micro-optical element on the left.

† Corresponding author: Andrew Forbes; tel: +27 12 841 2368; fax: +27 12 841 3152; email: aforbes1@csir.co.za

XVII International Symposium on Gas Flow, Chemical Lasers, and High-Power Lasers, edited by Rui Vilar, Olinda Conde, Marta Fajardo, Luís O. Silva, Margarida Pires, Andrei Utkin, Proc. of SPIE Vol. 7131, 71311E · © 2009 SPIE · CCC code: 0277-786X/09/$18 · doi: 10.1117/12.820058

In the case depicted in Fig. 1 the back reflector, which would usually be a spherical curvature mirror, is shown as a non–conventional diffractive optical element (DOE). If the phase profile of this element is chosen so as to differ from spherical curvature, then it is possible to select transverse modes other than the conventional Helmholtz–Gauss and Laguerre–Gauss modes. Since the laser beam intensity and phase is selected inside the laser by the DOE, this is often referred to as intracavity laser beam shaping. While it is well known that transverse modes may be selected by amplitude means, even for very complex mode patterns[1], this has disadvantages in that the round trip loss increases thus restricting such solutions to high gain lasers. Contrary to this, it has been shown that it is possible to use a DOE to select the resonant mode by means of phase rather than amplitude[2,3], with the potential for greatly reduced losses in the medium. DOEs manipulate light by diffraction rather than reflection or refraction, and thus have feature sizes of the order of the wavelength of the light; this complicates fabrication and may lead to errors in the desired surface profile. If the surface structure of the element is of a kinoform nature (continuous relief surface), then the DOE acts as a phase–only element, without any additional diffraction losses.

2. RESONATOR DESIGN

In this section we outline how the phase profile of the intracavity DOE is determined, and how this relates to the choice of the resonant mode inside the cavity.

2.1 Resonator concept

The method of using DOEs inside laser resonators was first proposed by Belanger and Pare[2,3], and which we outline briefly here for the convenience of the reader. Consider some arbitrary field that may be written in the form:

$$u(x) = \psi(x)\exp\left[-ik\phi(x)\right] \ , \tag{1}$$

where $k = 2\pi/\lambda$ is the wavenumber of the laser beam, λ is the wavelength, and $\psi(x)$ and $\phi(x)$ are the amplitude and phase of the electric field respectively. The action of a DOE in the form of a phase–only micro–optical mirror (as depicted in Fig. 1) is to transform the phase $\phi_1(x)$ of an incoming field to a new phase $\phi_2(x)$ of an outgoing field according to:

$$\phi_2(x) = \phi_1(x) - 2\phi_{DOE}(x) \ . \tag{2}$$

The salient point here is that this transformation takes place in a lossless manner, i.e., the outgoing amplitude $\psi_2(x)$ is unchanged. In particular, one can show[2] that if the phase mirror is not spherical, then the change in phase also depends on the incoming field distribution $\psi_1(x)$. Thus it is expected that a phase–only mirror will discriminate against those modes that do not have the correct distribution $\psi_1(x)$. By invoking the requirement that the mode must reproduce itself after one round trip one can easily show that the resulting restrictions on the phase of the DOE mirror is given by:

$$\int_{-\infty}^{\infty} x\left(\frac{\partial \phi_1}{\partial x}\right)\psi_1^2(x)dx = \int_{-\infty}^{\infty} x\left(\frac{\partial \phi_{DOE}}{\partial x}\right)\psi_1^2(x)dx \ , \tag{3}$$

from which we conclude that phase of the resonator eigenmode is the same as the phase of the DOE mirror, apart from a constant:

$$\phi_{DOE}(x) = \phi_1(x) - \phi_1(0) \ . \tag{4}$$

Combining Eqs. (2) and (4), and ignoring the constant phase offset, we see that

$$\phi_2(x) = -\phi_1(x) \ . \tag{5}$$

Therefore the reflected beam $u_2(x)$ is the phase–conjugate of the incoming beam, $u_2(x) = u_1^*(x)$ (note that the wavevector is also inverted in this design due to the normal incidence operation). In this resonator only a particular beam distribution is phase conjugated by the DOE mirror, so that the eigenmode of the resonator satisfies the criteria that its wavefront matches the phase of each mirror in the cavity.

If we describe the desired field at the output coupler as u_{OC}, then reverse propagating the field to the DOE mirror using the Kirchhoff–Fresnel diffraction equation yields the field at the mirror as

$$u_{DOE}(\rho, L) = -i^{n+1}(k/L)\exp(ikL)\exp\left(\frac{ik}{2L}\rho^2\right)\int_0^\infty u_{OC}(r)J_n\left(\frac{k\rho r}{L}\right)\exp\left(\frac{ik}{2L}r^2\right)rdr\ , \tag{6}$$

where we have assumed that the resonator is rotationally symmetric and of optical path length L. If after reflection off the DOE the field u_{DOE} is to reproduce u_{OC} at the output coupler, then the required phase for DOE mirror must be given by

$$\phi_{DOE} = phase[u^*_{DOE}(\rho, L)]\ , \tag{7}$$

with optical transfer function

$$t_{DOE} = \frac{u^*_{DOE}}{u_{DOE}}\ . \tag{8}$$

This is the basis by which custom resonators may be designed.

2.2 Super–Gaussian beams

There are many classes of flat–top beams that exhibit very similar propagation properties[4]. It has already been shown previously that such beams are propagation invariant in a non–linearly absorbing medium, but diverge in their intensity profile very rapidly under free space propagation[5,6]. In many classes of flat–top beam, the rate of the divergence may be controlled by a scale parameter closely coupled to the steepness of the edges and the flatness of the intensity profile at the centre of the beam.

The exact definition of a flat–top beam (FTB) is one with constant intensity in some well defined radius, and zero intensity elsewhere:

$$I_{FTB}(r) = \begin{cases} I_0, & r < w \\ 0, & r > w \end{cases}, \tag{9}$$

where w is the radial width of the beam. There are several functions used to approximate this. The well–know super–Gaussian beam (SGB) has an intensity profile given by:

$$I_{SGB}(r) = I_0 \exp\left(-2(r/w)^{2N}\right)\ . \tag{10}$$

When the order parameter N becomes large, $I_{SGB}(r) = I_{FTB}(r)$. In the special case that $N = 1$, the intensity profile is the standard Gaussian.

3. FOX–LI ANALYSIS

The designed axisymmetric DOE mirror is shown in Fig. 2(a), with associate output intensity given by Fig. 2(b). The element was designed for a CO_2 laser cavity of length $L = 1.772$ m, operating at a wavelength of $\lambda = 10.6$ µm. The DOE was designed so that a circular SGB of order $N = 10$ is generated at the output coupler, with $w_0 = 10$ mm; the phase at the output coupler was set to 'flat', i.e., $R(0) = \infty$, with the DOE mirror placed well within the Rayleigh range of the beam, $L/z_r \sim 0.6$. Note that the surface height is modulated every 10.6 µm in height, or one complete wavelength, corresponding to a 2π phase shift of the light. An intracavity aperture was added to the resonator in the form of a 15 mm radius circular aperture placed at the DOE mirror in order to mimic the limited spatial extent of the electrodes of the CO_2 laser.

Calculations of the mode were performed using the Fox–Li method[7], starting from spontaneous emission (background noise). The field at the output coupler was computed for each complete round trip, and the losses for the ith round trip were calculated as:

$$Loss = 1 - \frac{\gamma_i}{\gamma_{i-1}} \tag{11}$$

where γ is the energy contained in the field.

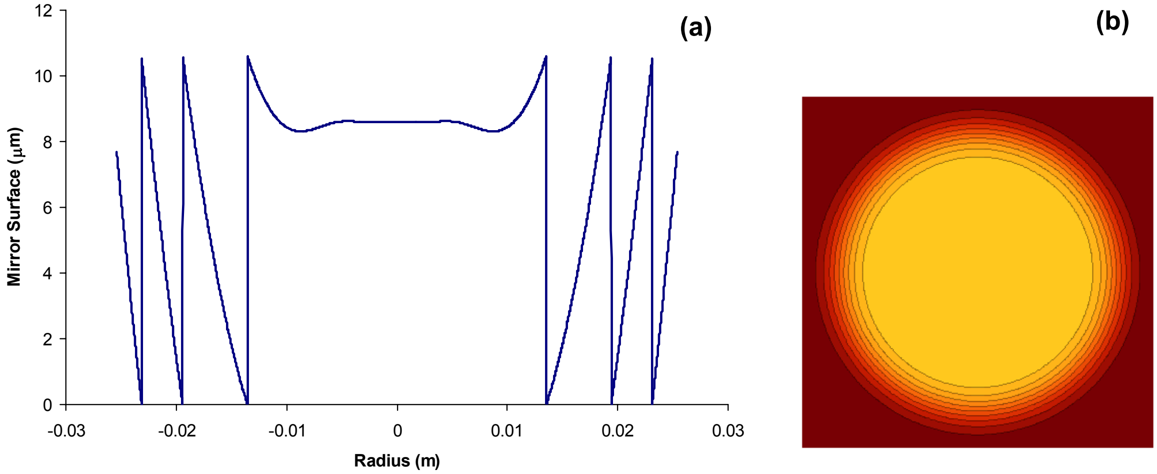


Fig. 2. Example of a DOE for outputting a SGB of order N = 10: (a) DOE mirror surface, and (b) contour plot of the expected beam intensity at the output coupler, showing a uniform intensity central region and steep edges.

The modal build–up was computed starting from a background noise signal. After approximately 250 round trips the losses of the field stabilized, indicating that a stable mode had formed. The final loss of the stable mode per round trip was found to be 0.2%, which is close the theoretically predicted 0% loss for this conjugating resonator.

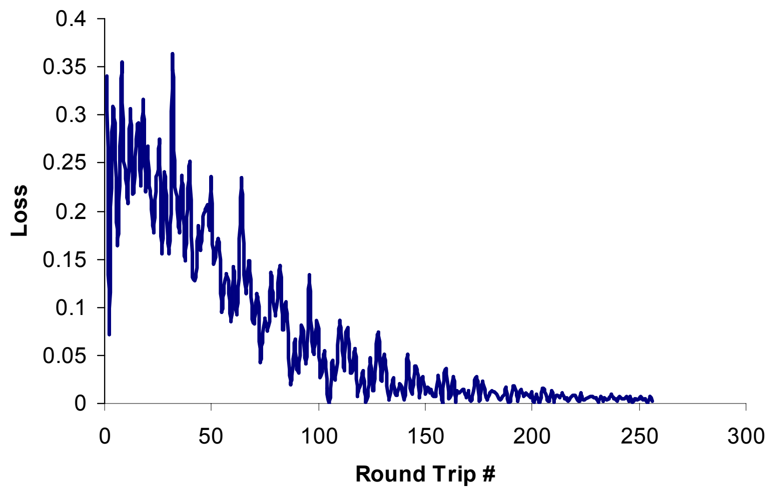


Fig. 3. Round trip loss starting from noise (high loss) finally converging to low loss after ~250 round trips.

At convergence, the wavefronts on both mirrors match that of the oscillating beam, as expected. The phase of the beam at the output coupler is shown in Fig. 4(a) and is clearly the desired ‘flat’ wavefront. Also shown in Fig. 4(b) is the intensity profile of the stable mode, showing a very good approximation to the desired flat–top beam. It is interesting to consider mode competition in such resonators, a topic already reported on by some of the authors. Unsurprisingly, the losses increase as the order parameter is detuned away from the design beam order. However, as expected one can not easily distinguish between these classes of beams when their order is selected such that the intensity profile is similar to that of a SGB of N = 10. However, the ability of the resonator to discriminate against those modes not matching this intensity profile is very evident, with losses that are orders of magnitude higher when the order parameter is detuned. However, a small error in the phase of the mirror has a significant influence on the output mode from the resonator. From this it is clear that fabrication errors are an important likely contributor in determining the stable mode of the cavity. We have therefore propose a DOE mirror with a static phase that can be adjusted with the aid of a deformable mirror to compensate for such problems[8].

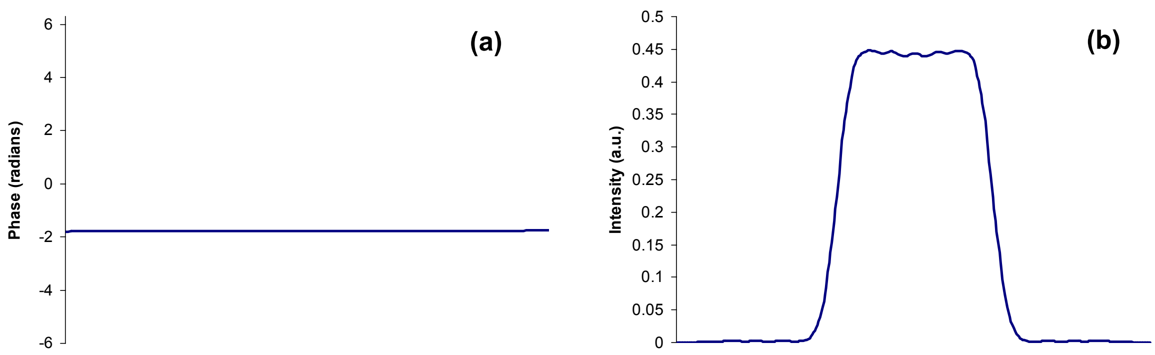


Fig. 4. (a) Phase of the oscillating mode at the output coupler, showing a flat wavefront, and (b) stable mode output intensity from the resonator.

4. PROPAGATION

One of the consequences of selecting a mode of a given order is the distance over which it will propagate without distortion. One can readily show that increasing the order of the SGB decreases the peak intensity[5]. The increase in edge steepness with increasing order also introduces higher spatial frequencies onto the beam, thus resulting in faster intensity changes during propagation, as shown in Fig. 5.

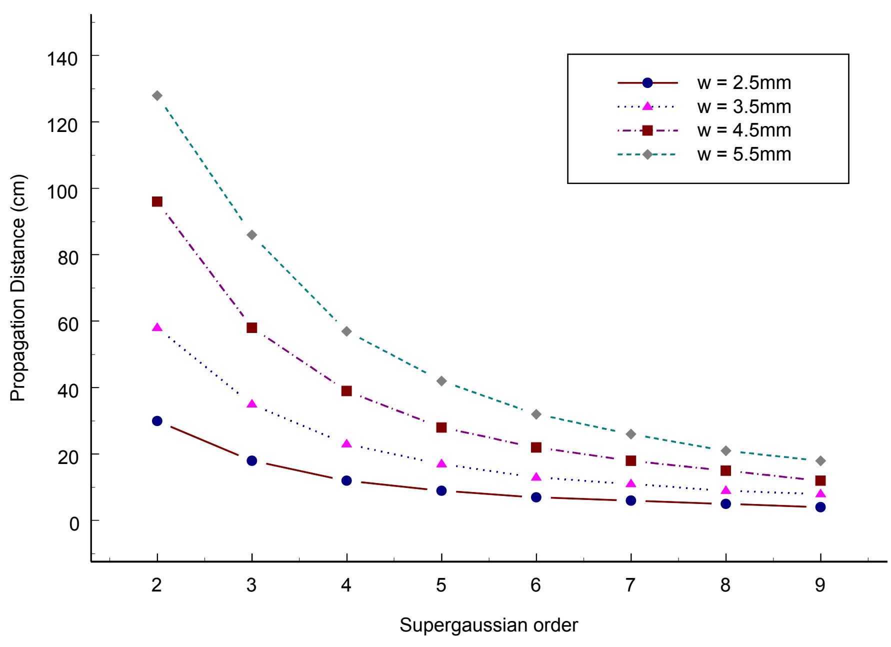


Fig. 5. A Plot of the propagation distance before the SGB changes shape by more than 10% rms. As the super-Gaussian order is increased, so this distance decreases.

Figure 5 shows the distance over which a super–Gaussian beam may propagate before the flat central region changes from the ideal by more than 10% rms; we will consider this the distance over which the SGB may be propagated without significant changes to its shape. This distance is a function of both the beam size and the beam order. As the order of the SGB increases, so the propagation distance without change decreases. For very high orders of the SGB, the dominating factor is the order parameter, and one observes changes in the beam shape over as little as only a few centimeters. In a practical delivery system that makes use of such beams, the output from the resonator therefore needs to be relay imaged to the target, with appropriate magnification – free space propagation will seldom work.

5. EXPERIMENTAL RESULTS

The above mentioned DOE mirror was manufactured and installed in a TEA CO_2 laser. The laser was designed to yield a nominal pulse energy of 5 J and an average power of 1500 W at a repetition rate of 300 Hz. The multimode and single mode Gaussian beam propagation characteristics of the laser were measured as a baseline. Hereafter, the propagation properties of the SGB were determined. Table 1 summarizes the beam propagation parameters for the various laser beams. From Table 1 it can be seen that the multimode beam produces the highest pulse energy but also has the highest divergence and M^2 values. The single mode Gaussian beam in contrast has low divergence and M^2 values which is ideal for beam propagation but however only contains approximately 4% of the energy that is available in the multimode beam. The SGB exhibits divergence and M^2 values that are lower than for multimode case but not as low as for the single mode Gaussian beam. The SGB however has 85% of the energy that is contained in the multimode beam. When the beam area of the multimode beam and the SGB are compared it is found that the area of the SGB beam is approximately 70% of the area of the multimode beam. Taking into account the fact that the energy in the SGB is 84% of the energy that is contained in the multimode beam it can be concluded that the SGB resonator design yields a better energy extraction than in the multimode case. The SGB will therefore be quite suitable for applications where a flat–top beam with high pulse energy and favorable beam propagation parameters are required.

Parameter	**Multimode**	**TEM_{00}**	**Super Gaussian**
M^2 x-axis	21.3	1.06	22
M^2 y-axis	28.7	1.08	16.8
Divergence x-axis	9.4 mrad	1.98 mrad	8.02 mrad
Divergence y-axis	10.7 mrad	2.02 mrad	6.51 mrad
Pulse energy	6.3 J	250 mJ	5.3 J

Table 1. Measured beam propagation parameters for TEA CO_2 laser.

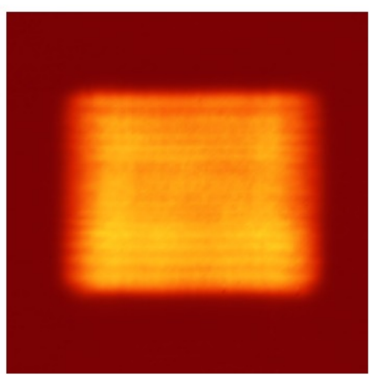


Fig. 6. Measured multimode beam profile

Fig. 6 shows the measured multimode beam profile and Fig. 7 the measured single mode Gaussian beam profile of the laser. The measured SGB profile for the laser is shown in Fig. 8, as produced using the DOE resonator. Figure 8 shows that with the presence of the DOE optic in the cavity the laser yielded a single mode flat–top super-Gaussian beam; this has been confirmed by observing an unchanging temporal pulse across the beam profile. The flat–top beam is not completely flat as what would be ideal and some high intensity peaks are present in the beam. This could potentially be attributed to non–uniformities that exist in the laser gain over the gain volume area.

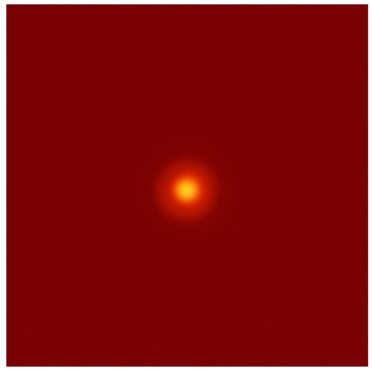


Fig. 7. Measured single mode Gaussian beam profile

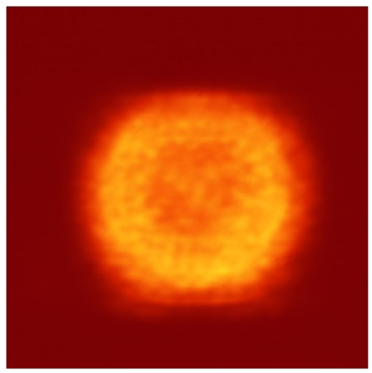
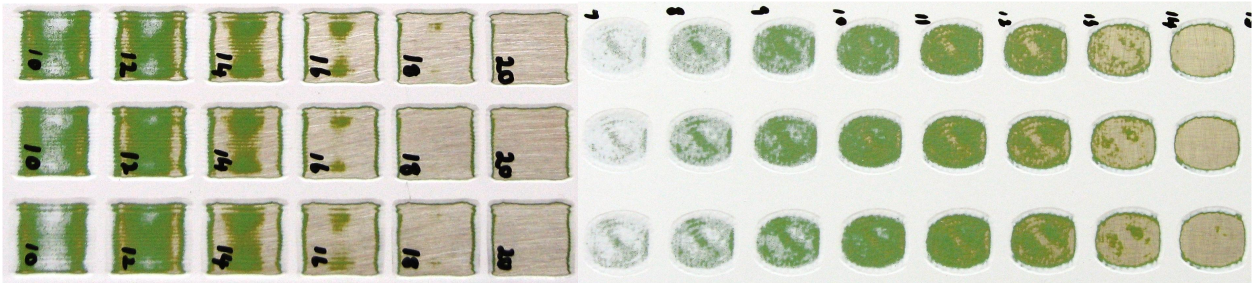


Fig. 8. Measured SGB profile

6. APPLICATIONS

The flat–top super-Gaussian beam could ideally be used in a laser based paint stripping application. For laser based paint stripping with a TEA CO_2 laser, high pulse energy, good beam propagation characteristics and a uniform energy distribution in the beam are desirable to deliver the laser beam to the target and to uniformly ablate the target surface. The single mode Gaussian beam has favorable propagation characteristics but does not contain enough energy to do the paint stripping. The multimode beam is more ideal as it has high pulse energy and an almost flat–top like profile but the propagation parameters are not ideal. The multimode beam also exhibits the modes that it is made up of, and this can be seen as intensity fluctuations in the beam while it is used in the paint stripping application.

Figure 9 shows the application of a multimode beam for paint stripping. The results shown in Fig 9 were recorded by keeping the paint stripping target stationary at a position and applying a number pulses to the target. The target was then moved to a new position and the number of laser pulses increased. This process was repeated until the substrate was exposed. The higher intensities in the multimode beam are clearly visible in Fig. 8(a) during the paint stripping process and one can see that in some areas paint is already removed from the substrate, while in other areas of the beam the top coat is still visible. The horizontally aligned intensities are due to the mode structure of the beam and the vertical intensities due to non–uniformity of the gain in the gain area. The application of the flat-top super-Gaussian beam is shown in Fig. 8(b). It is evident that the top coat of paint and primer are more evenly ablated with the super–Gaussian beam. The super–Gaussian beam therefore poses distinct advantages over the multimode and single mode Gaussian beams in the application of paint stripping.



(a) (b)

Fig. 8. Examples of the application of (a) multimode and (b) flat-top super-Gaussian beams in laser based paint stripping

7. CONCLUSION

We have outlined the design approach for an optical resonator that produces as the stable transverse mode a flat–top laser beam, by making use of an intra–cavity phase–only diffractive mirror as the mode selective device. A diffractive mirror for the resonator was designed, fabricated and then verified in a TEA CO_2 laser. Furthermore, the propagation of the SGB was compared to the propagation for the multimode and single mode Gaussian beams for the particular laser under study. The generated SGB was also used in a paint stripping application to demonstrate the advantages that a SGB holds for such an application.

8. ACKNOWLEDGEMENTS

This work was supported by grants from the DST-INNOVATION FUND as part of project T60003, *Environmentally friendly laser paint stripping method for aircraft*. The authors would also like to thank M.J. Botha for his participation in performing the laboratory work.

REFERENCES

[1] Litvin I.A., and Forbes A., "Bessel–Gauss resonator with internal amplitude filter," *Opt. Commun*., **281**, 2385–2392 (2008).

[2] Belanger P.A., and Pare C., "Optical resonators using graded-phase mirrors," *Optics Letters*, **16**(14), 1057–1059 (1991).

[3] Pare C. and Belanger P.A., "Custom laser resonators using graded-phase mirrors," *IEEE Journal of Quantum Electronics*, **28**(1), 355–362 (1992).

[4] Shealy D.L., and Hoffnagle J.A., "Laser beam shaping profiles and propagation," *Applied Optics*, **45**(21), 5118–5131 (2006).

[5] Forbes A., Strydom H.J., Botha L.R., and Ronander E., "Beam delivery for stable isotope separation," *Proc. SPIE* **4770**, 13–27 (2002).

[6] Forbes A., "Laser beam propagation in non-linearly absorbing media," *Proc. SPIE* **6290**, 629003 (2006).

[7] Fox A.G., Li T., "Resonant modes in a maser interferometer," *Bell Syst. Tech. J*., **40**, 453–488 (1961).

[8] Long C.S., Loveday P.W. and Forbes A., "A piezoelectric deformable mirror for intra-cavity laser adaptive optics", *Smart Structures and Materials 2008: Industrial and Commercial Applications of Smart Structures Technologies, Proc. SPIE* **6930**, 69300Y–1 (2008).